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LOW COST FABRICATION DEVELOPMENT FOR OXIDE DISPERSION STRENGTHENED ALLOY VANES

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FINAL REPORT

MATERIAL AND PROCESS TECHNOLOGY LABORATORIES
AIRCRAFT ENGINE GROUP
GENERAL ELECTRIC COMPANY
CINCINNATI, OHIO 45215

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16. Abstract

Viable processes were developed for secondary working of oxide dispersion strengthened (ODS) alloys to near-net shapes (NNS) for aircraft turbine vanes. These processes were shown capable of producing required microstructure and properties for vane applications.

Material cost savings of 40 to 50% are projected for the NNS process over the current procedures which involve machining from rectangular bar. Additional machining cost savings are projected.

Of three secondary working processes evaluated, directional forging and plate bending were determined to be viable NNS processes for ODS vanes. Extrusion of shaped preforms was not, on the basis of high preform cost and excessive workability demands on the ODS materials. Directional forging was deemed most applicable to high pressure turbine (HPT) vanes with their large thickness variations while plate bending was determined to be most cost effective for low pressure turbine (LPT) vanes because of their limited thickness variations. Since the F101 LPT vane had been selected for study in this program, development of plate bending was carried through to establishment of a preliminary process.

Preparation of ODS alloy plate for bending was found to be a straight forward process using currently available bar stock, providing that the capability for reheating between roll passes is available.

Advanced ODS-NiCrAl and ODS-FeCrAl alloys were utilized on this program. Workability of all alloys was adequate for directional forging and plate bending, but only the ODS-FeCrAl had adequate workability for shaped preform extrusion. The ODS-NiCrAl alloys were capable of attaining the vane required (100) longitudinal texture, while the ODS-FeCrAl was not and was dropped early in the program.

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FOREWORD

The work described herein was conducted by the Aircraft Engine Group, General Electric Company under NASA Contract NAS3-19710. The NASA Project Manager was C. P. Blankenship, NASA-Lewis Research Center. The General Electric Program Manager was E. J. Kerzicnik. The Technical Manager was P. G. Bailey. R. J. Perkins was the Principal Investigator. TRW Inc., Cleveland, Ohio was the major subcontractor for the near-net shape work with D. J. Moracz as program engineer and C. R. Cook program manager.

ABSTRACT/SUMMARY

Viable processes were developed for secondary working of oxide dispersion strengthened (ODS) alloys to near-net shapes (NNS) for aircraft turbine vanes. These processes were shown capable of producing required microstructure and properties for vane applications.

Material cost savings of 50 to 60% are projected for the NNS process over the current procedures which involve machining from rectangular bar. Additional machining cost savings are projected.

Of three secondary working processes evaluated, directional forging and plate bending were determined to be viable NNS processes for ODS vanes. Extrusion of shaped preforms was not, on the bases of high preform cost and excessive workability demands on the ODS materials. Directional forging was deemed most applicable to high pressure turbine (HPT) vanes with their large thickness variations while plate bending was determined to be most cost effective for low pressure turbine (LPT) vanes because of their limited thickness variations. Since the F101 LPT vane had been selected for study in this program, development of plate bending was carried through to establishment of a preliminary process.

Preparation of ODS alloy plate for bending was found to be a straight forward process using currently available bar stock, providing that the capability for reheating between roll passes is available.

Advanced ODS-NiCrAl and ODS-FeCrAl alloys were utilized on this program. Workability of all alloys was adequate for directional forging and plate bending, but only the ODS-FeCrAl had adequate workability for shaped preform extrusion. The ODS-NiCrAl alloys were capable of attaining the vane required (100) longitudinal texture, while the ODS-FeCrAl was not and was dropped early in the program.

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EXECUTIVE SUMMARY

The purpose of this program was to develop near-net shape (NNS) processes and achieve significant cost savings for Oxide Dispersion Strengthened (ODS) turbine vanes. The program emphasized advanced ODS alloys and their application to an ODS low pressure turbine (LPT) vane.

ODS alloys have advantages over cast materials because of greater strengths at high temperatures, higher melting points and microstructural stability nearly to their melting points. Their use has resulted in significant savings in fuel consumption through reduced or eliminated cooling air required for cast vanes. The application of ODS vanes has been hampered by their high cost. One of the major cost factors is the current low material yields.

Currently, ODS vanes are machined out of rectangular bar stock with material usage rates of ten percent or less. Figure A depicts the situation for both vanes and bands as prepared for an advanced F101 aircraft turbine engine.

The program was divided into two tasks. In the first task several secondary working processes were evaluated and one selected as most cost effective for the F101 LPT vane. In addition, in Task I, several advanced ODS-NiCrAl and ODS-FeCrAl alloys were evaluated and the selections narrowed for Task II.

Of the three secondary working processes evaluated in Task I, depicted in Figure B, directional forging and plate bending were determined to be viable NNS processes for ODS vanes. Extrusion of shaped preforms was not, on the bases of high preform cost and excessive demands on the workability of the ODS alloys. Directional forging was deemed most applicable to high pressure turbine (HPT) vanes with their large thickness variations, while plate bending was determined to be most cost effective for LPT vanes and HPT bands because of their limited thickness variations in the direction of curvature. Since the F101 LPT vane had been selected for study in this program, development of plate bending was carried through establishment of preliminary process and preform specifications. A bent plate NNS and a finish machined vane are shown in Figure C.

Preparation of ODS plate for bending was found to be a straight forward process using currently available bar stock, providing that the capability for reheating between passes is available. Plate is not a current commercial ODS product.

Advanced ODS-NiCrAl alloys (HDA 8077, MA 757, and YD NiCrAl) and ODS-FeCrAl (MA 956) were utilized on this program. Workability of all alloys was adequate for directional forging and plate bending but only the ODS-FeCrAl had adequate workability for shaped preform extrusion.

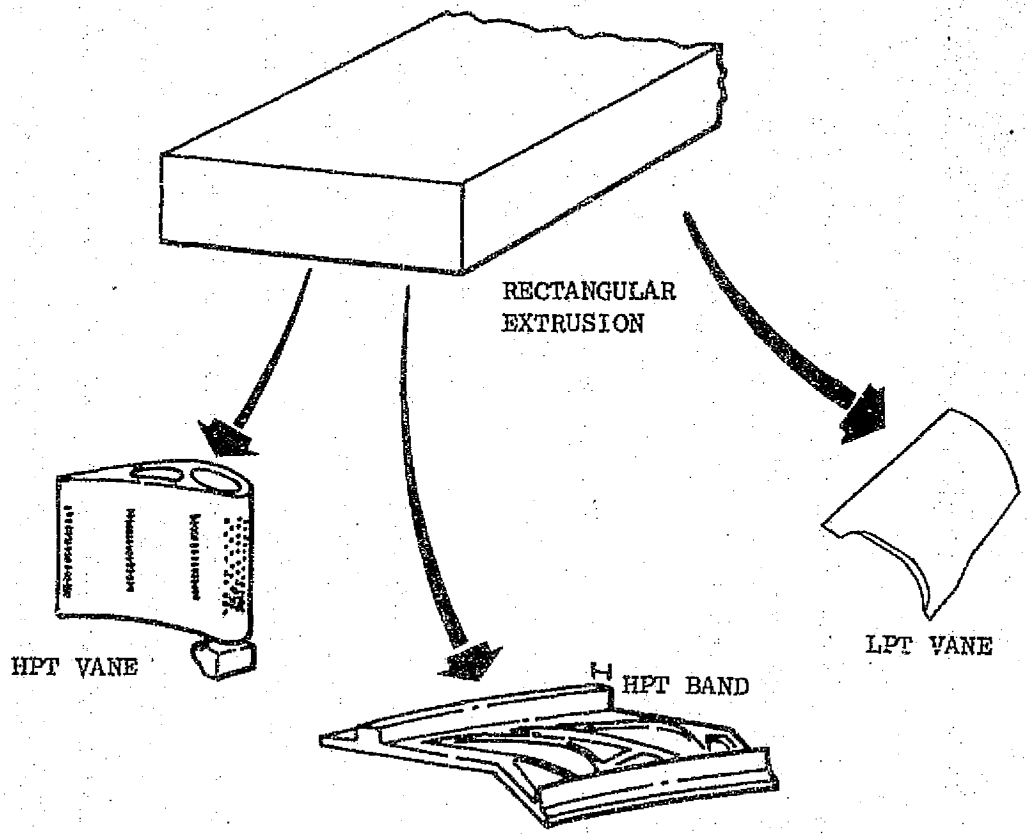


Figure A Current F101 ODS Alloy Material Utilization

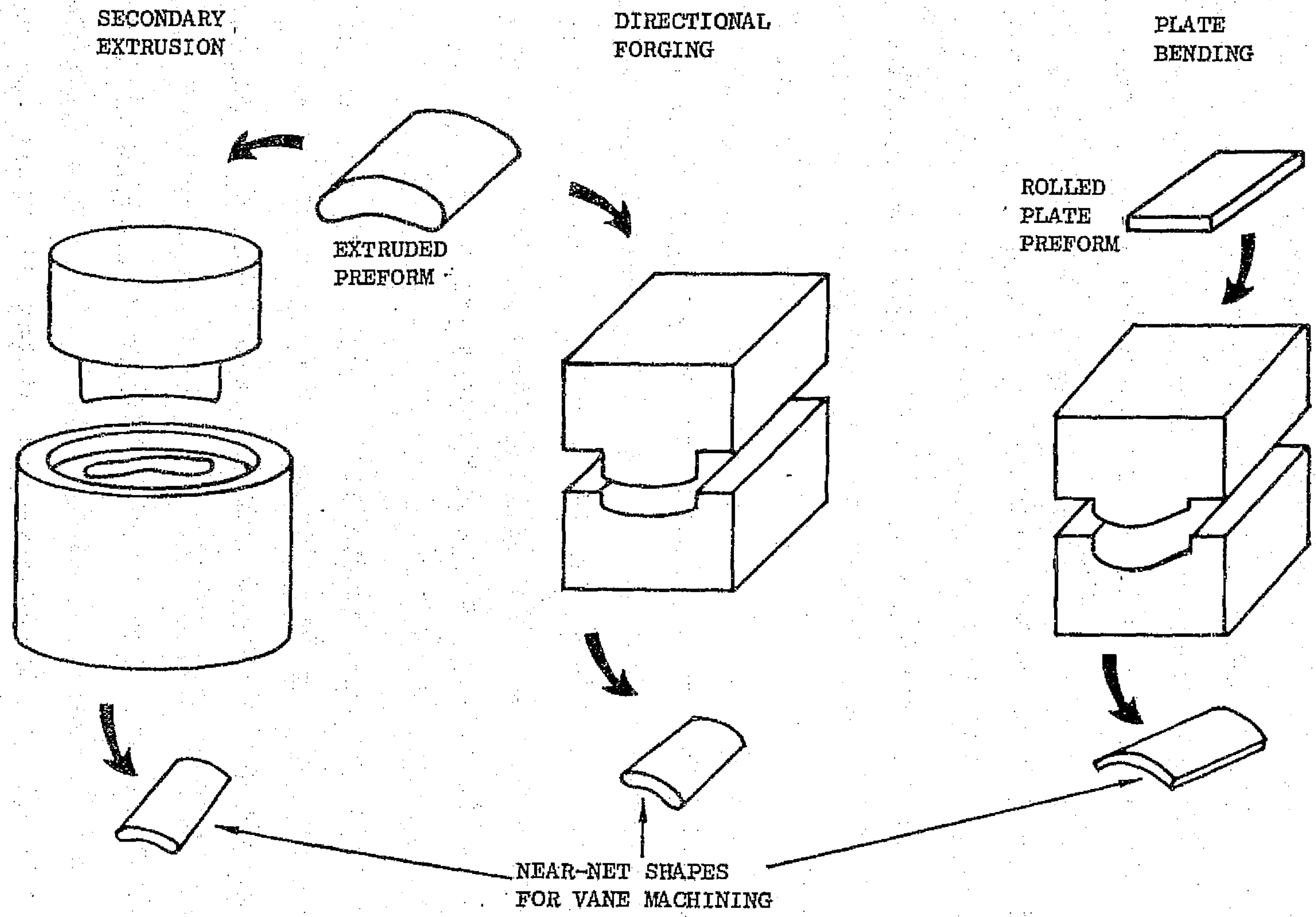
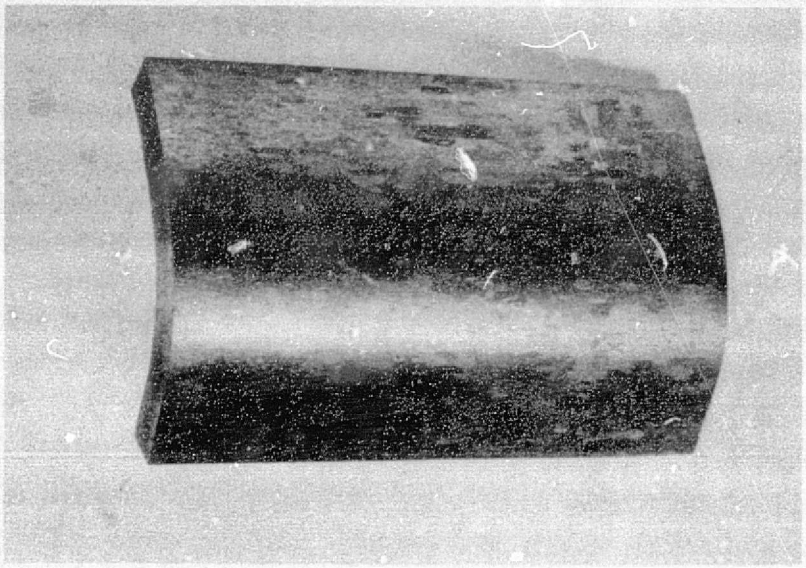


Figure B Task I Near-Net Shape Processes



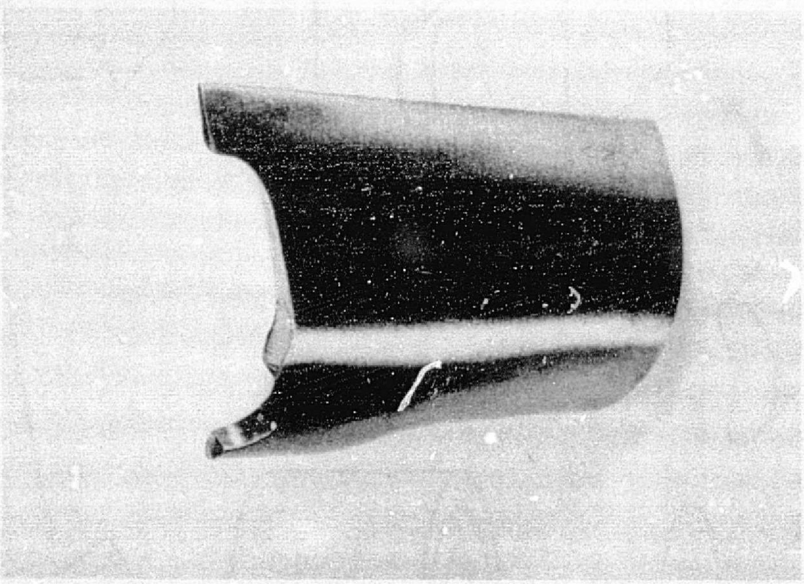


Figure C Bent Near-Net Shape and Finished LPT Vane

The ODS-NiCrAl alloys were capable of attaining the vane required (001) low modulus texture, while the ODS-FeCrAl was not and was dropped early in the program.

The program was successful in developing an LPT NNS process capable of an estimated 60 percent material cost savings. Additional machining cost savings of about 19 percent also are expected.

TRW Inc. did the extrusion, forging and plate bending on the program. ODS material suppliers included Huntington Alloys Inc. (MA 757 and MA 956), Special Metals Corp. (YD NiCrAl) and the Stellite Division of Cabot Corp. (HDA 8077).

1.0 INTRODUCTION

The major advantages of ODS alloy vane materials over cast materials are their greater strengths at high temperatures, higher melting points and microstructural stability. (1) Their use has resulted in approximately 1.5% savings in fuel consumption through reducing or eliminating cooling air required for cast vanes and bands in an advanced engine.

It has been shown by most successful experimenters in the ODS field that good properties are dependent on achieving coarse recrystallized grains of the proper crystallographic texture. (2) Coarse grain size is a requisite to achieve high temperature strength in most ODS alloys. Low modulus textures are needed for best thermal fatigue resistance. Well distributed stable submicron dispersoids with small interparticle spacings are not enough to achieve properties. Development of thermomechanical processes which produce the proper recrystallized structures are most important in obtaining the microstructural features desired in ODS alloys.

ODS alloy powders are made by chemical and mechanical mixing of matrix and dispersoid constituents (3,4,5). These powders can be consolidated to mill product by extrusion and forging followed by various conventional metal shaping processes. (6,7,8)

The current process for ODS vanes comprises extrusion for powder consolidation followed by hot rolling to a rectangular shape and subsequent recrystallization. The latter two steps achieve the required microstructure for creep and thermal fatigue resistance.

Attempts to improve the low material utilization inherent in machining vanes from rectangular shapes by direct extrusion to vane shapes has not achieved much success to date for a variety of reasons. Some are equipment related, others result from the difficulties in reliably producing uniform microstructures in nonuniform shapes.

The purpose of this program was to establish by secondary working processes a near-net shape (NNS) process for the F101 LPT vane and achieve a significant (about 40%) manufacturing cost savings.

The program was divided into two tasks. In the first task several secondary working processes were evaluated including directional forging, extrusion and data bending. In the second task, the best process was selected for verification and the product evaluation.

Advanced ODS alloys selected for this program included HDA8077, YDNiCrAl, MA757 and MA956.

2.0 NEAR NET SHAPE PROCESS DEVELOPMENT

The basic approach of Task I was designed to determine ODS alloy primary process conditions and configurations compatible with secondary NNS processes. The total working of the ODS alloy is critical in the maintenance of the desired microstructure.

2.1 Selection of Subcontractor

TRW, Cleveland, Ohio, was selected as the NNS vendor because of their technical expertise in ODS materials and a practical business interest in participation. TRW over the years has participated in a number of government-sponsored forging programs with ODS alloys.[1] In addition, TRW has developed considerable expertise in generating precision shapes in superalloys. TRW was deemed capable of carrying out all the NNS processes envisioned for this program.

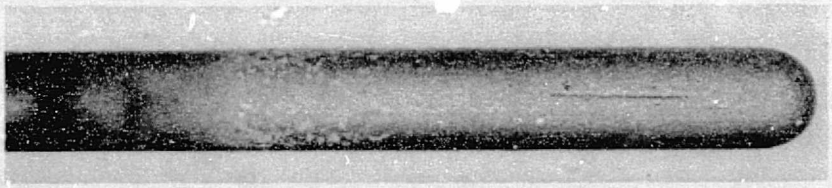
2.2 Selection of ODS Alloys

Advanced ODS nickel and iron base alloys containing aluminum were selected for this program primarily because of their improved oxidation resistance established in another NASA program[2] and are listed below.

Alloy	Nominal Composition	Supplier
HD8077	Ni-16Cr-4Al $1Y_2O_3$	Cabot
YDNiCrAl	Ni-16Cr-4Al-$1Y_2O_3$	Special Metals
MA757	Ni-16Cr-4Al-$1Y_2O_3$	Huntington Alloys
MA956	Fe-20Cr-5Al-$.5Y_2O_3$	Huntington Alloys

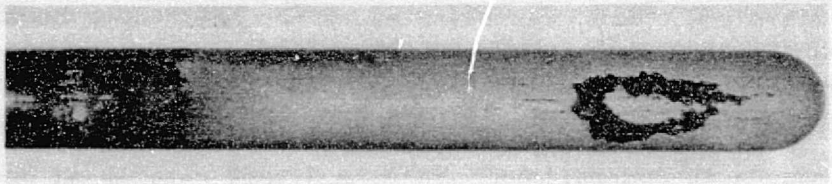
The beneficial effects of the aluminum addition are shown in Figure 1. Pin shaped specimens 6.35 mm (1/4 in.) diameter by 63.5 mm (2.5 in.) long or MA956, HDA 8077, YDNiCrAl and MA754 were exposed in cyclic burner rig 2200°F, Mach 1 oxidation testing. The aluminum bearing MA956, HDA 8077 and YDNiCrAl ODS alloys after 252 hours indicate very good oxidation resistance. No change in shape was detected. The MA754 (nominally Ni-20Cr-0.3Al-0.5Ti-0.6Y_2O_3) pin after 208 hours eroded to a 2.44 mm (3/32 in.) diameter indicating relatively poor oxidation resistance.

Further description of the alloy's configuration and microstructural conditions is provided in the following conversion process sections.



2X

MA956



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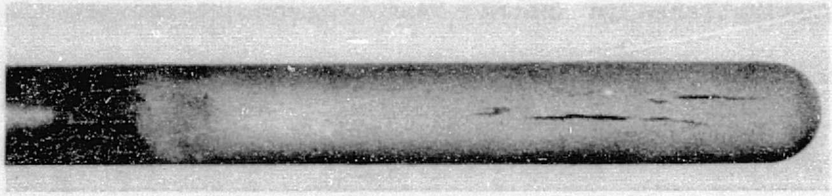
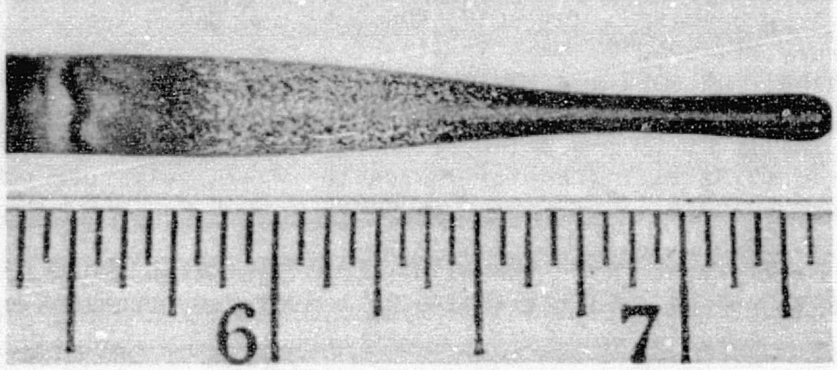
HDA8077



2X

YD-NiCrAl



MA754 2X

Figure 1 Beneficial Effects of Aluminum Additions for Improved Oxidation Resistance of ODS Alloys. All Alloys exposed in Mach 2 Cyclic Oxidation Testing at 1200°C for Approximately 250 hr

2.3 Material and Economic Requirements

Current ODS alloys preparation consist of mechanically alloying prealloyed and/or elemental powders with Y_2O_3 dispersoid in an attritor, canning in a hollow cylinderical steel container and extrusion for consolidation. Rectangular shapes are hot flat rolled to final dimensions. The unique high temperature properties of ODS alloys are achieved by proper thermomechanical processing to achieve a controlled grain size and shape (high aspect ratio) and a preferred crystallographic orientation (texture). Hot working the material in a single direction achieves the critical strain necessary for the formation of the preferred low modulus (001) longitudinal texture in a subsequent recrystallization heat treatment.

Extrusion of large billet sizes and simple shapes is the first step in preserving process economics.

To achieve a highly cost effective ODS alloy NNS turbine vane process(es) several material and process requirements must be met. Economically, a viable NNS process has to significantly improve material utilization without incurring significant additional process cost as compared to the current vane manufacturing process. An added benefit would accrue if vane machining costs could be lowered also.

Currently, vanes are machined from heavy rectangular shaped ODS alloy bars resulting in poor utilization (e.g. 10%) of expensive material as is shown in Figure 2.

The secondary conversion techniques investigated in this program to establish NNS feasibility were designed to maintain maximum process control. ODS alloys are sensitive to material flow direction, reduction level and process temperature. These conditions are controlled by preform and conversion tooling design and will be discussed in detail in the various NNS processing sections. NNS processes should not degrade the ODS alloy properties, should be inexpensive and production oriented (simple, rapid, reproducible).

2.4 Task I Selected Near-Net Shape Techniques

ODS alloy preform and NNS configurations selected for the Task I feasibility investigation are shown in Figure 3. The NNS closely approximates that of an F101 LPT vane. Uniformly thick preform and NNS configurations minimize deleterious lateral and tangential material flows and variation in reduction level. A "gullwing" preform extrusion as shown in Figure 4 was designed to fulfill the economical and extrusion state-of-art requirements. The double repetitive kidney shape increases the cross-sectional area facilitating a large economical starting billet size (8" dia.) and allows the necessary extrusion ratios required to achieve a critically strained ODS alloy at the one-half inch final preform thickness.

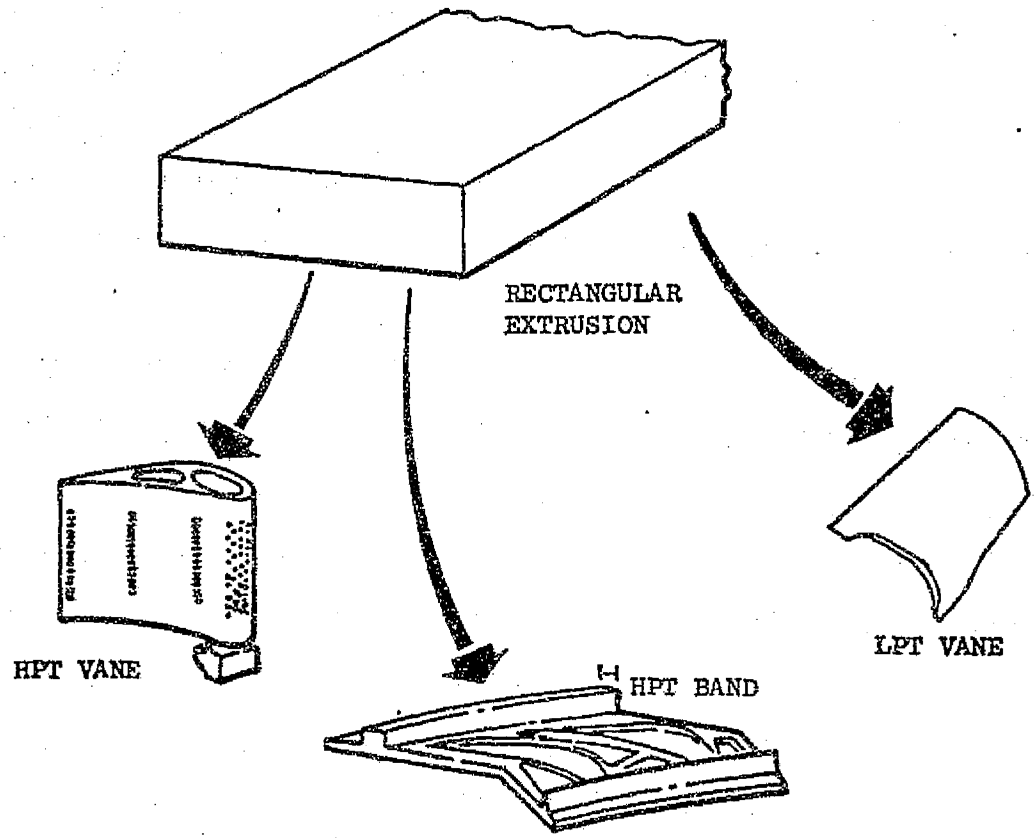
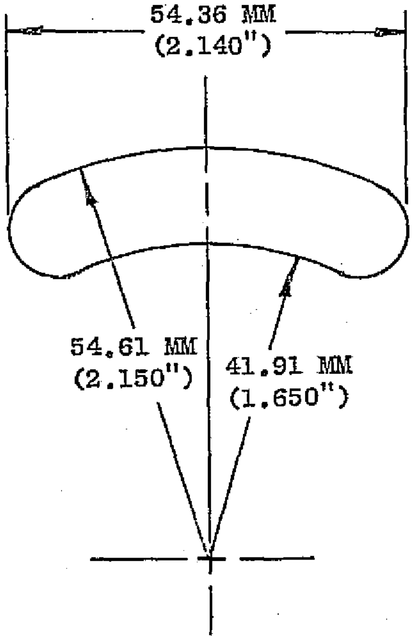
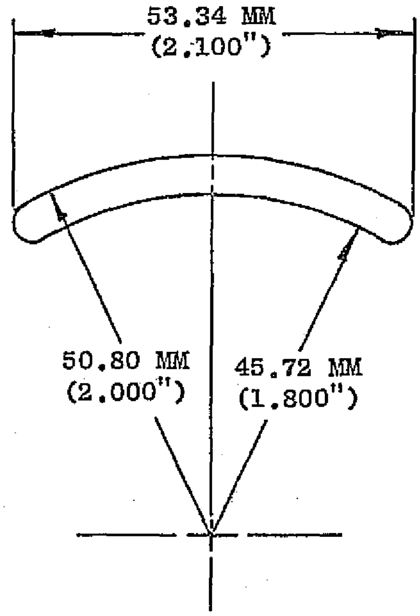


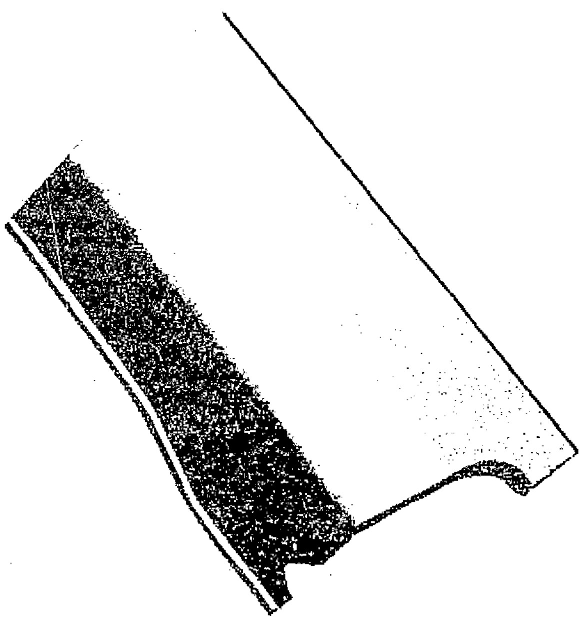
Figure 2 Current F101 ODS Alloy Material Utilization



(a) PREFORM CROSS-SECTION
LENGTH = 43.18 MM (1.700")

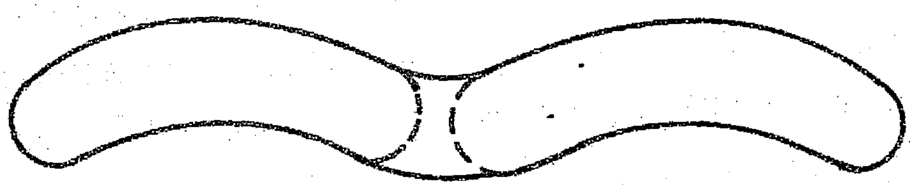


(b) NEAR NET VANE SHAPE CROSS-SECTION
LENGTH = 82.35 MM (3.250")



(c) FINISHED MACHINED LOW
PRESSURE TURBINE VANE

Figure 3 Task I Selected Preform, NNS and Finished Vane



"GULLWING" EXTRUSION

Figure 4 Gullwing Extrusion & Preform Configuration

2.4.1 Extrusion

Selected Alloys and Configurations

Two ODS alloys in several process conditions as indicated in Table I were used in the extrusion investigation. Three HDA 8077 gullwings were prepared by Cabot Corporation using conditions imparting various levels of residual energy. Total thermomechanical processing must be considered in working ODS alloys. Metallurgical effects generated in primary processing have an influence on the response of these alloys to secondary processing. Gullwing No. 1 was produced from an eight inch diameter billet extruded at 1038°C (1900°F) and a 14 to 1 reduction ratio. This condition was anticipated to produce the critical strain (residual energy) necessary to achieve the optimum grain structure in a subsequent recrystallization heat treatment. Gullwing No. 2, also eight inches in diameter, extruded at 1093°C (2000°F), 14 to 1 reduction ratio and was designed to be underworked because of the higher process temperature. Gullwing No. 3 was a six inch diameter billet extruded at 1038°C (1900°F) and a 9 to 1 ratio. This extrusion was processed to be in an under-worked condition through the use of a low reduction ratio. Each billet was to provide six feet of double kidney preform material. The HDA 8077 gullwing extrusions are shown in Figure 5. Outer appearance of the gullwings after pickling off the mild steel extrusion jacket was poor (heavily dimpled). This surface condition was caused by gross oxidation of the mild steel can during the four hour heatup for extrusion. Although the surface condition was not judged to be a serious consequence and could be corrected by providing better protection against oxidation of the billet prior to extrusion. Cross-sectional shape was reasonably close to that desired. Considerably less than the expected six feet of each material was received because of cracking in all three extrusions. The cracking was believed to be a result of an inadvertent water quenching the gullwings from a black heat for rapid expediting. Sufficient quantities were salvaged to conduct the initial investigations.

Macrostructures of the gullwings in the as-extruded and recrystallized condition are shown in Figure 6 and the microstructure in Figure 7. Recrystallization was obtained by heat treating at 1200°C (2200°F), 1260°C (2300°F) and 1315°C (2400°F) for one hour at each temperature. All three extrusions contained a dual microstructure, i.e., there was an envelope of large grains about one-eighth inch in thickness around the periphery of the gullwings and the central regions had relatively small grains. The large grains had a low aspect ratio (length/diameter) in contrast to a high aspect ratio of the small grains. Texture was generally the desirable (001) except for some small grains that appear by high reflectivity to be a higher modulus crystallographic orientations. Those grains were too small for Laue back reflection orientation analysis.

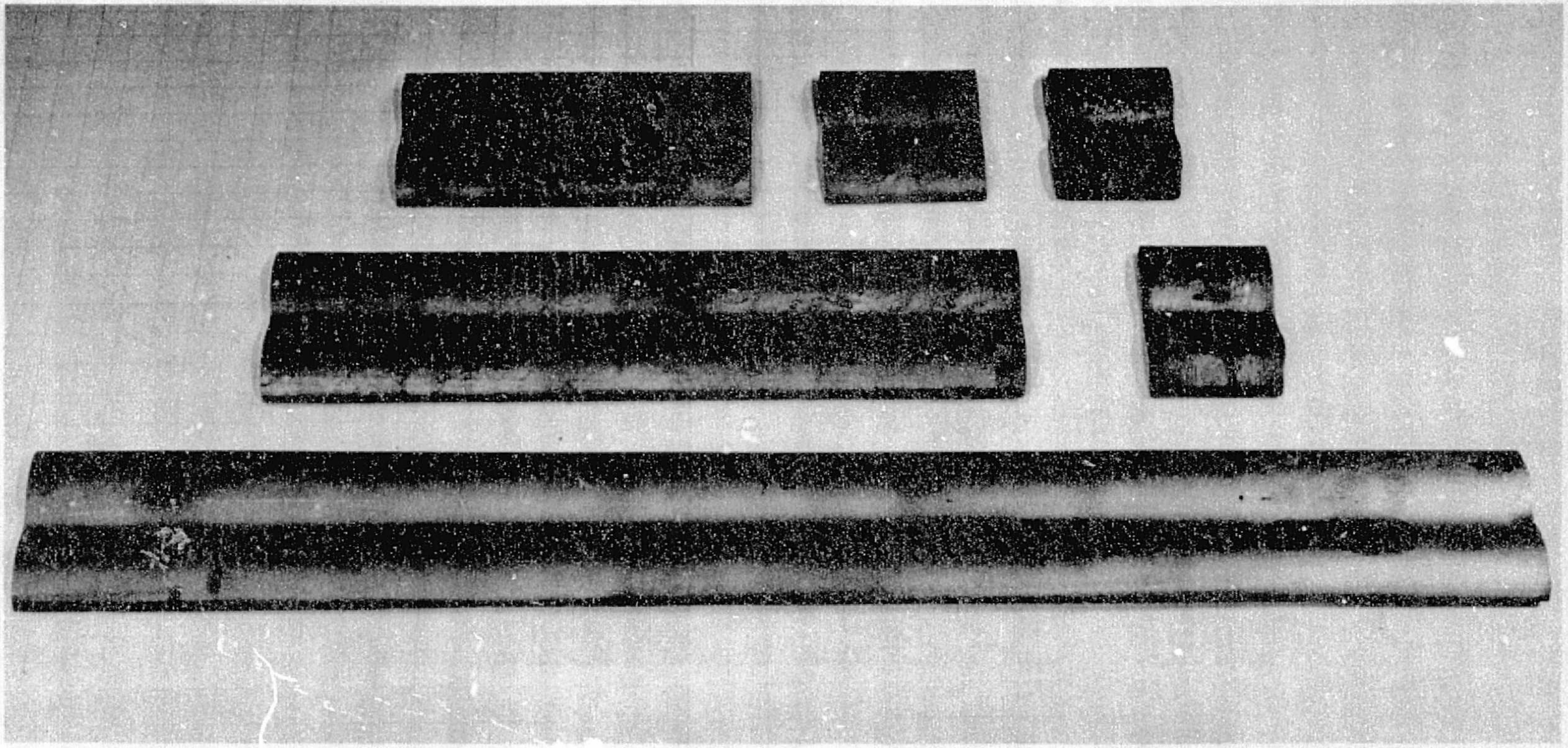
The MA956 alloy was included in the program as a high risk material which would have a very substantial payoff if successful. Previous experimentors (10,11) have failed to achieve the low modulus (001) orientation in the BCC structure. FeCrAl alloys have high temperature oxidation and corrosion resistance superior to most known alloys. The MA 956 was procured in as-hot-rolled 30.5 mm (1.2 inches) thick x 73.7 mm (2.9 inches) wide rectangular bar.

TABLE I. ODS ALLOY PROCUREMENT FOR NNS EXTRUSION AND FORGING INVESTIGATIONS

			Extrusion Conditions			
S.N.	Alloy[1]	Vendor	Shape	Temperature, °C (°F)	Billet Diameter, cm (in)	Ratio
1	HDA 8077	Cabot	Gullwing	1038 (1900)	20.3 (8)	14:1
2	HDA 8077	Cabot	Gullwing	1093 (2000)	20.3 (8)	13;1
3	HDA 8077	Cabot	Gullwing	1038 (1900)	15.2 (6)	9:1
5	MA 956	Huntington Alloys Inc.	Rectangular	(2)	(2)	(2)

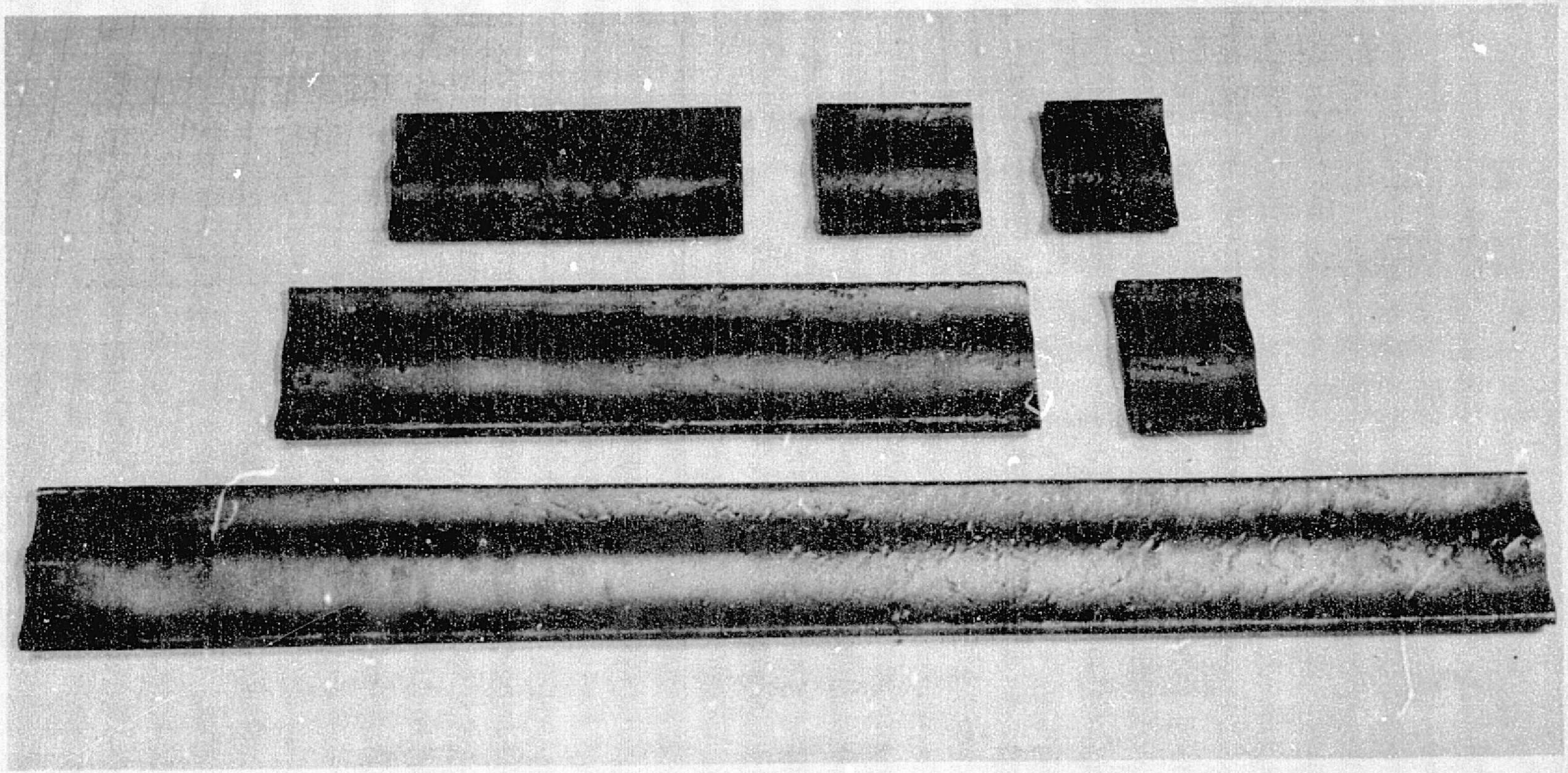
(1) As-worked (unrecrystallized) condition.

(2) Extrusion conditions not provided by vendor.



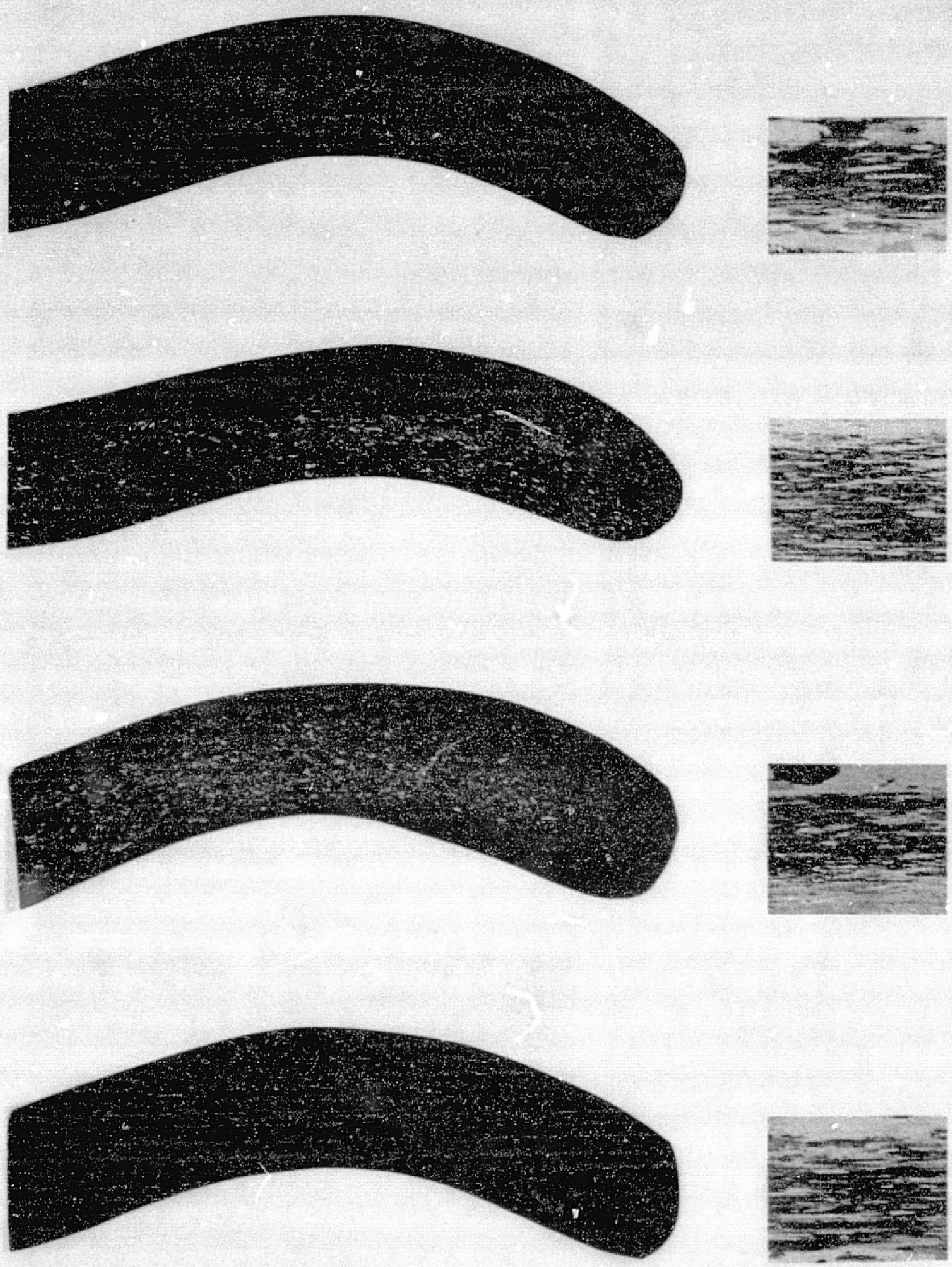
(a) CONVERSE SIDES

Figure 5 HDA 8077 Gullwing Extrusions



(b) CONCAVE SIDES

Figure 5 HDA 8077 Gullwing Extrusions



NO. 1

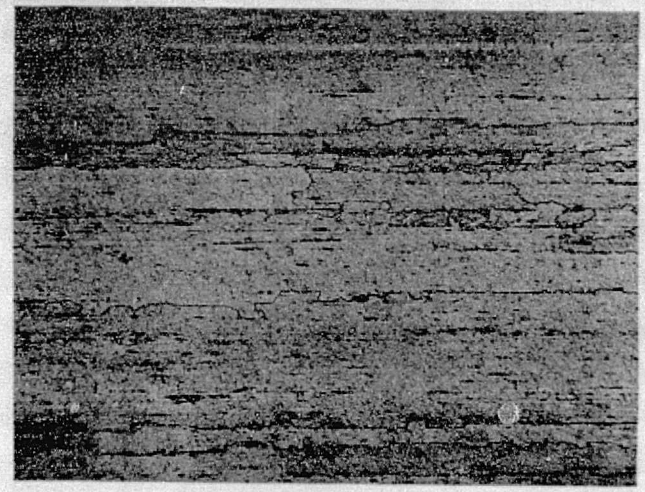
NO. 2

NO. 3

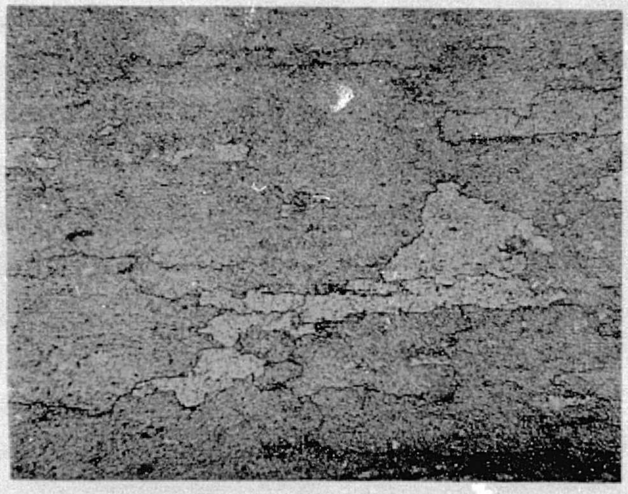
NO. 4

(a) TRANSVERSE SECTIONS (b) LONGITUDINAL SECTIONS

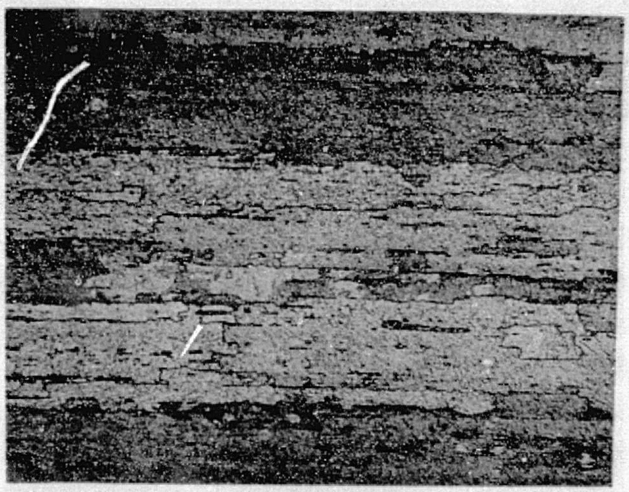
Figure 6 Macrostructures of HDA 8077 Gullwing Extrusions in Recrystallized Condition



NO. 1 EXTRUDED + Rx 100X

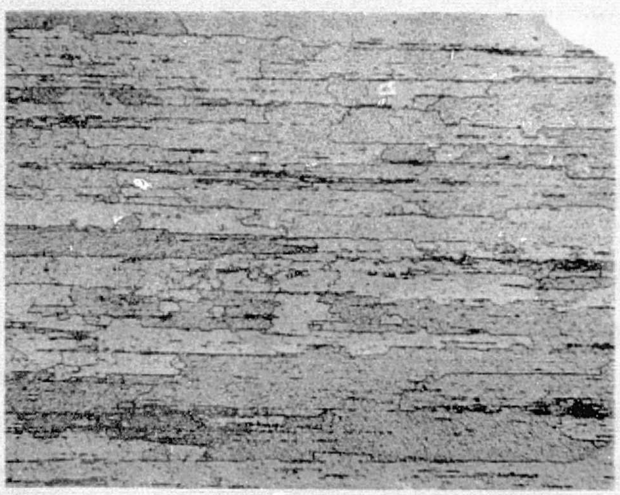


100X



NO. 2 EXTRUDED + Rx 100X

100X



NO. 3 EXTRUDED + Rx 100X

(a) LONGITUDINAL

100X

(b) TRANSVERSE

Figure 7. Microstructures of the HDA 8077 Gullwing Extrusions in the Recrystallized Condition

NNS Tooling and Equipment Design

Extrusion was performed in a closed die system as shown in Figure 8. A feature of this design which was different from typical extrusion tooling was the orifice or die opening has a die angle of 120° except at the ends where a shear die concept was used. This was to restrict lateral flow of the ODS alloy during extrusion. The extrusion tooling built from A1S1 H21 tool steel and installed in a 1334 MN (150 ton) hydraulic press is shown in Figure 9.

Experimental Procedure

The NNS tooling design was tested by successfully extruding low alloy steel and Inconel 718. A series of ODS alloy closed die extrusion trials were conducted as indicated in Table II. MA 956 and HDA 8077 alloy kidney shaped preforms (Figure 3) were heated to temperatures of 1038°C (1900°F), 1093°C (2000°F) and 1149°C (2100°F) in an electric furnace and extruded to a 50% reduction (2.5 to 1) at rates varying from 5.1 mm (0.2 inches) to 40.6 mm (1.6 inches) per second. All the preforms were unclad but were glass coated to reduce the heat loss from the part to the warm (700°F) tooling. Graphite spray or Fiske swab lubricant was used on the tooling. Extrusion pressures were between 689 MPa (100 ksi) and 896 MPa (130 ksi) for those that extruded successfully without stalling the press. Although transfer time from the furnace to die was only about five seconds, the time required to achieve full pressure was an additional ten seconds.

The extrusion results are shown in Figure 10. All HDA 8077 extrusions exhibited nose and tail burst and severe shear cracks. No significant changes were observed when extruding at different temperatures. Frequent "hanging up" in the die, incomplete extrusion and finally a die failure were observed. Changes in lubrication and coatings did not affect the extrudability of the HDA 8077 material. The MA 956 extruded very well at 1149°C (2100°F) with no evidence of surface defects. Extruding at lower temperatures produced some shear cracks. Recrystallization, macroetching and examiniation of the MA 956 parts indicated the desirable low modulus (001) texture was not achieved.

2.4.2 Directional Forging - Campaign I

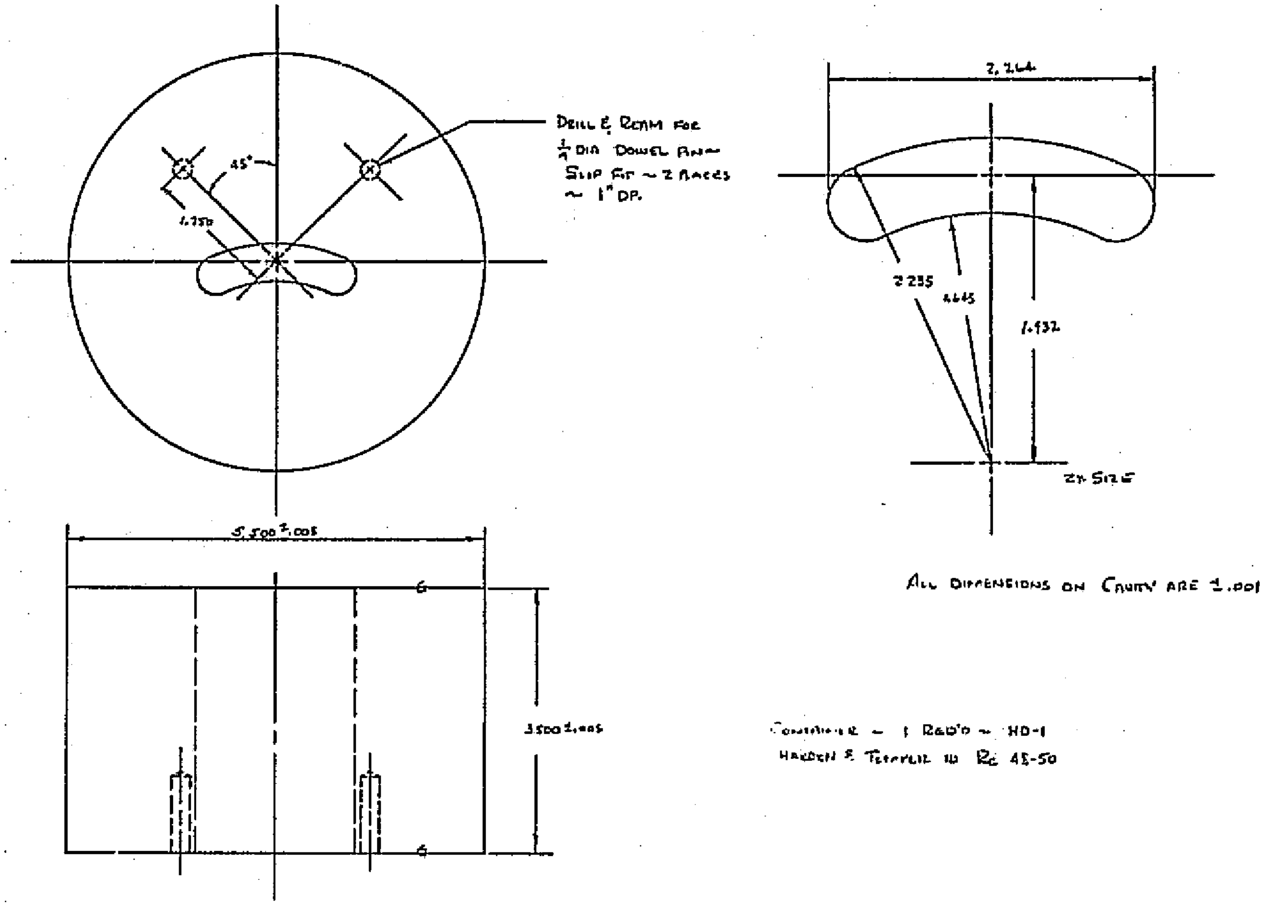
ODS Alloys and Configurations

The forge process investigation consisted of two separate campaigns. Table I lists the ODS alloys, preparations and shapes used in forging Campaign I and were the same as in the extrusion investigation except for the addition of lower Y_2O_3 content HDA 8077 materials. A fourth HDA 8077 gullwing extrusion (No. 4) containing an intermediate Yttria level (1.3%) was prepared and some HDA 8077 single kidney shaped extruded material, 20.3 mm (0.8 inches) thick x 63.5 mm (2.5 inches) wide, containing a low level (0.6%) yttria were used. Gullwing No. 4 exhibited a dual microstructure after recrystallization comparable to the other three gullwing. The 0.6% yttria bearing material when subjected to the recrystallization heat treatment produced the desired (001) texture throughout. The ODS alloys prepared with 0.6% and 1.3% yttria were incorporated to establish the effects of dispersoid content on forgeability.

TABLE II. CLOSED-DIE EXTRUSION TRIALS

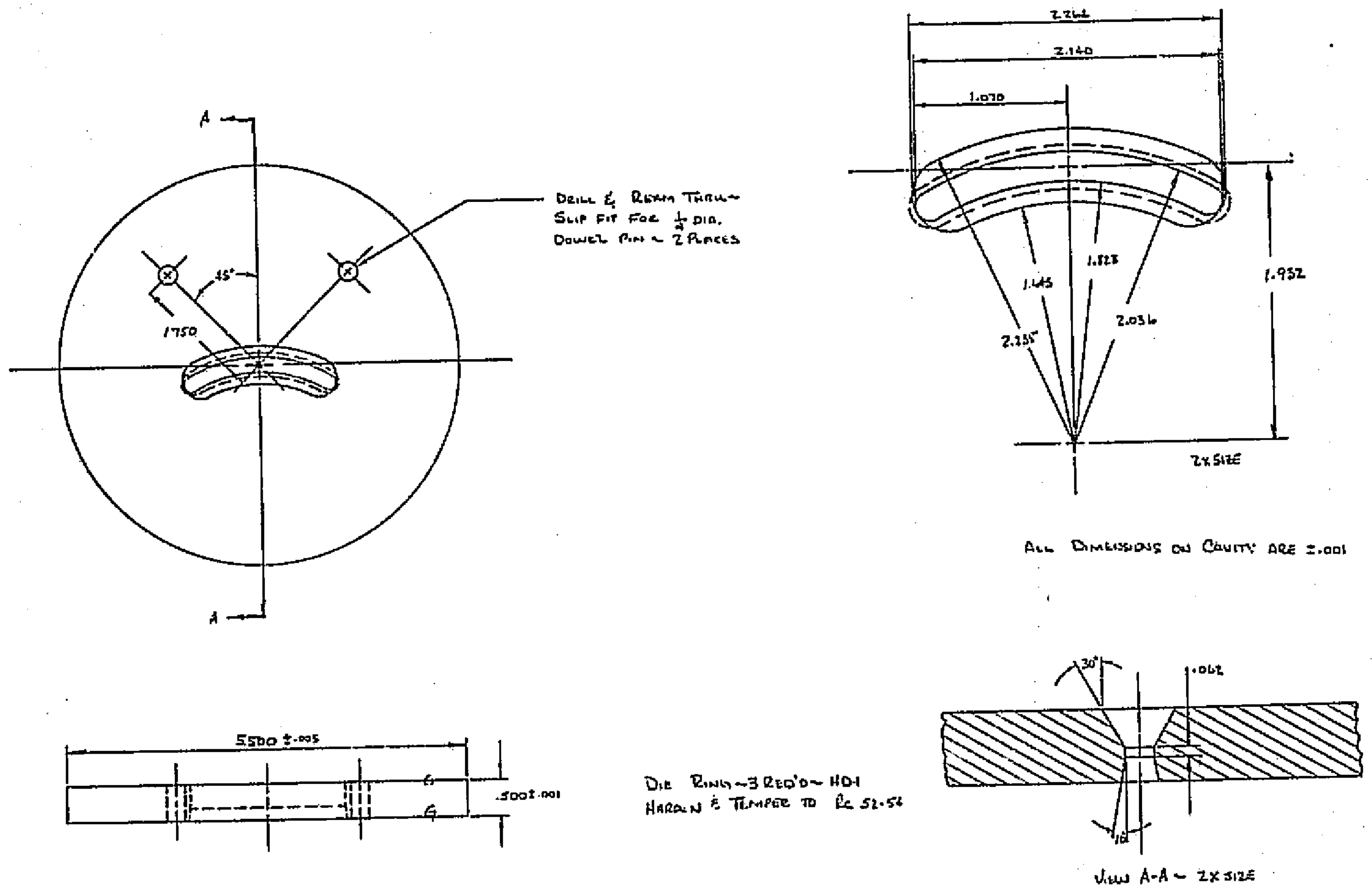
Preform No.	Material	Gullwing Extr. No.	TRW Extrusion °C (°F)	Soak Time, Minutes	Extrusion Speed mm/sec (in./sec)	Appearance
8	ODS FeCrAl	5[1]	1149 (2100)	15	38 (1.5)	Good
9	ODS NiCrAl	1	1149 (2100)	16	38 (1.5)	Severely cracked
10	ODS NiCrAl	3	1149 (2100)	15	38 (1.5)	Severely cracked
11	ODS FeCrAl	5[1]	1093 (2000)	15	38 (1.5)	Three edge checks, 6.4 mm (1/4") deep
12	ODS NiCrAl	1	1093 (2000)	20	38 (1.5)	Severely cracked
13	ODS NiCrAl	3	1093 (2000)	55	38 (1.5)	Severely cracked
14	ODS FeCrAl	5[1]	1038 (1900)	15	38 (1.5)	One edge check, 7.9 mm (5/16") deep
15	ODS NiCrAl	1	1038 (1900)	15	38 (1.5)	Severely cracked
16	ODS NiCrAl	3	1038 (1900)	15	38 (1.5)	Severely cracked
17	ODS NiCrAl	2	1038 (1900)	15	5 (0.3)	Severely cracked
18	ODS NiCrAl	2	1149 (2100)	15	5 (0.2)	Severely cracked

(1) Kidney preforms were prepared from rectangular bar.



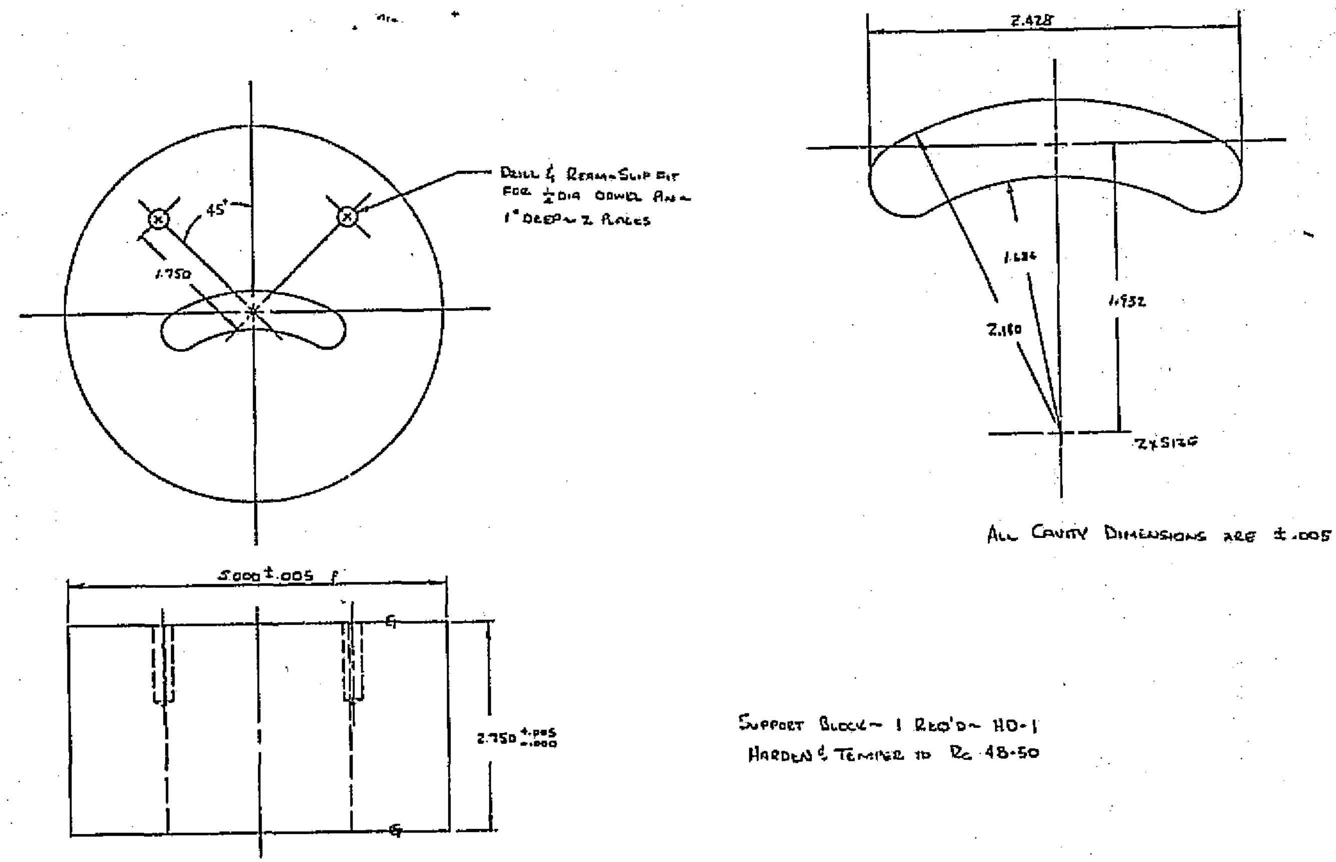
(a) CONTAINER

Figure 8 ODS Alloy Extrusion Tooling Designs



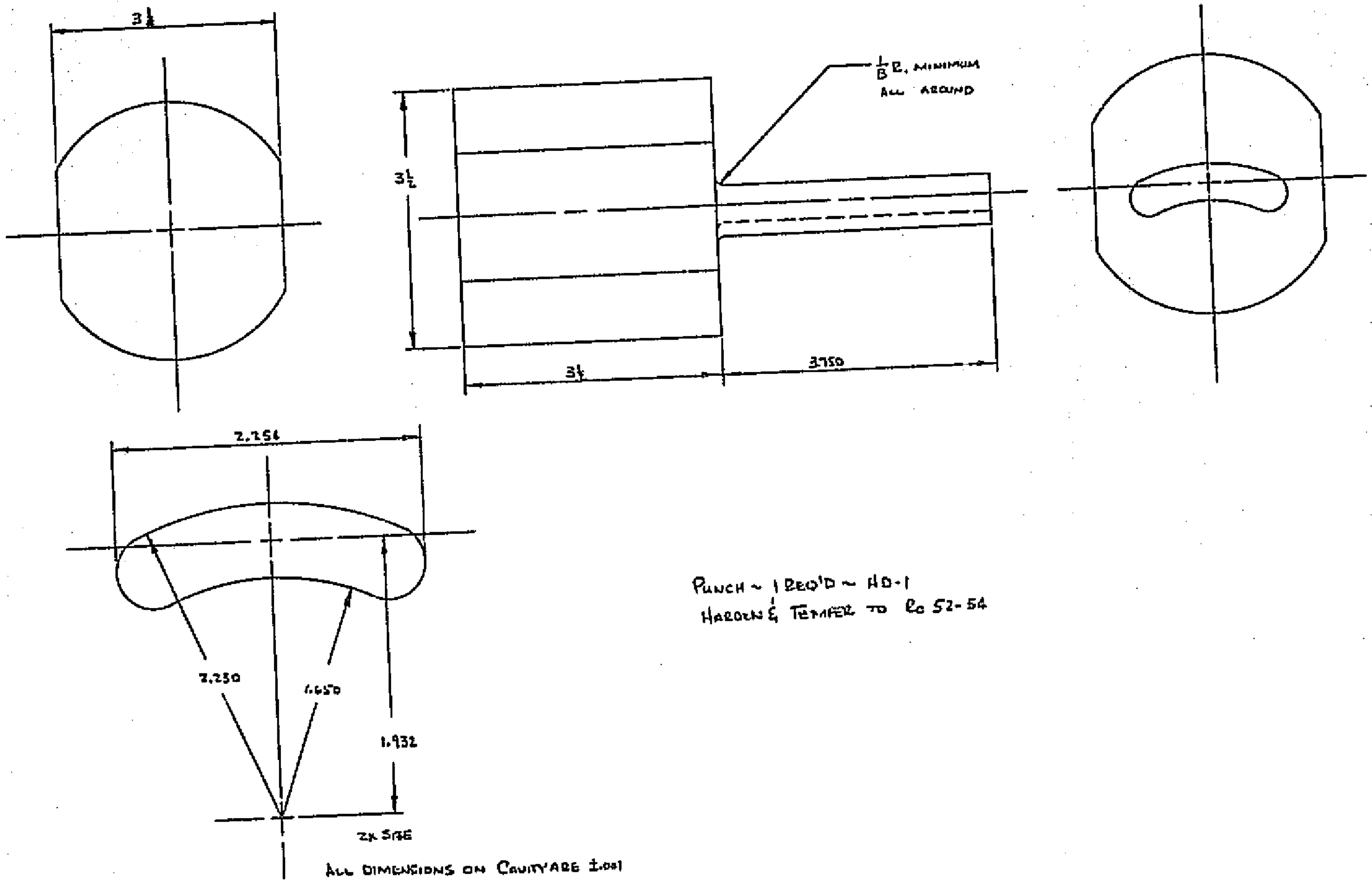
(b) DIE RING

Figure 8 (Continued)



(c) SUPPORT BLOCK

Figure 8 (Continued)



(d) PUNCH

Figure 8 (Continued)

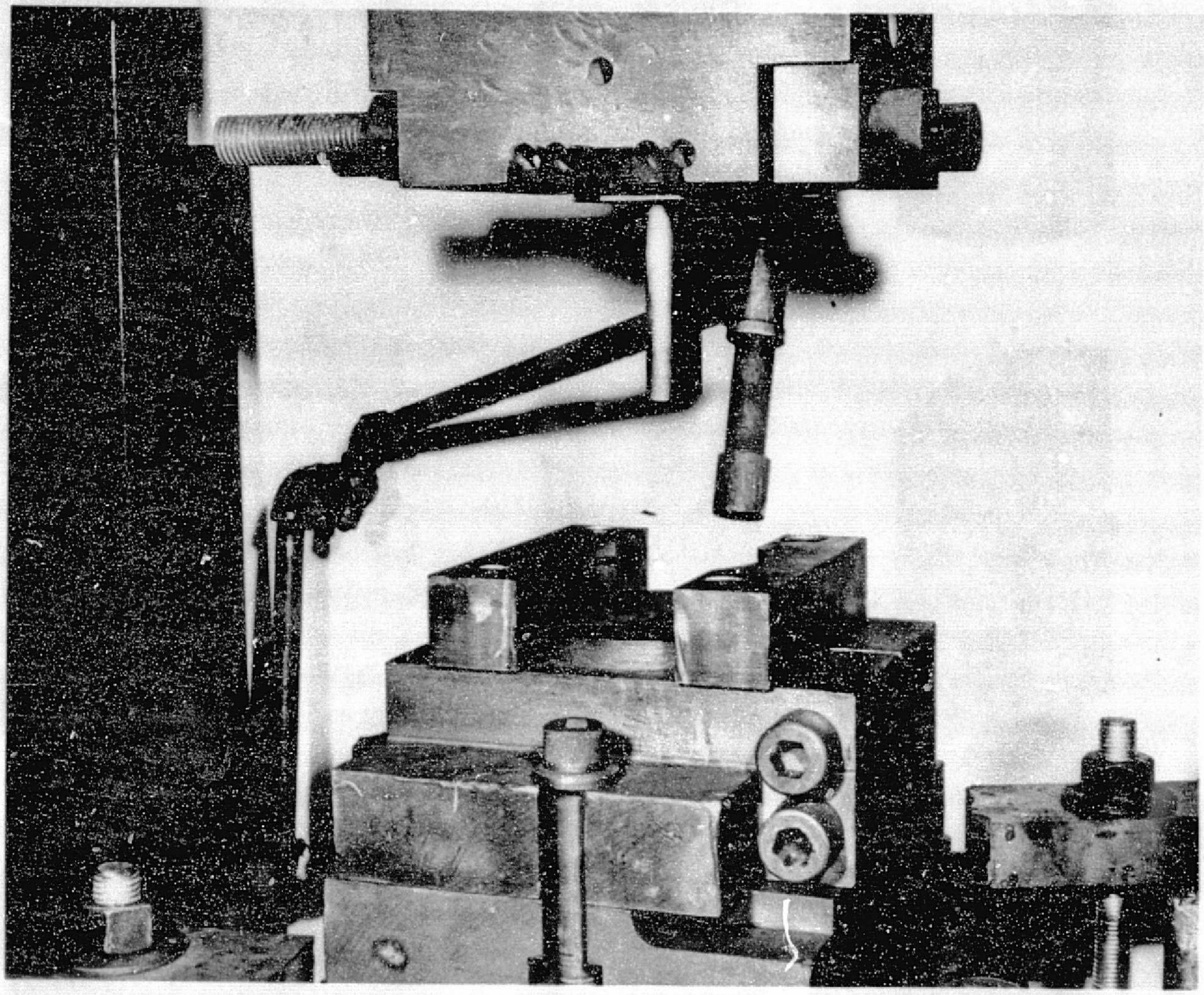
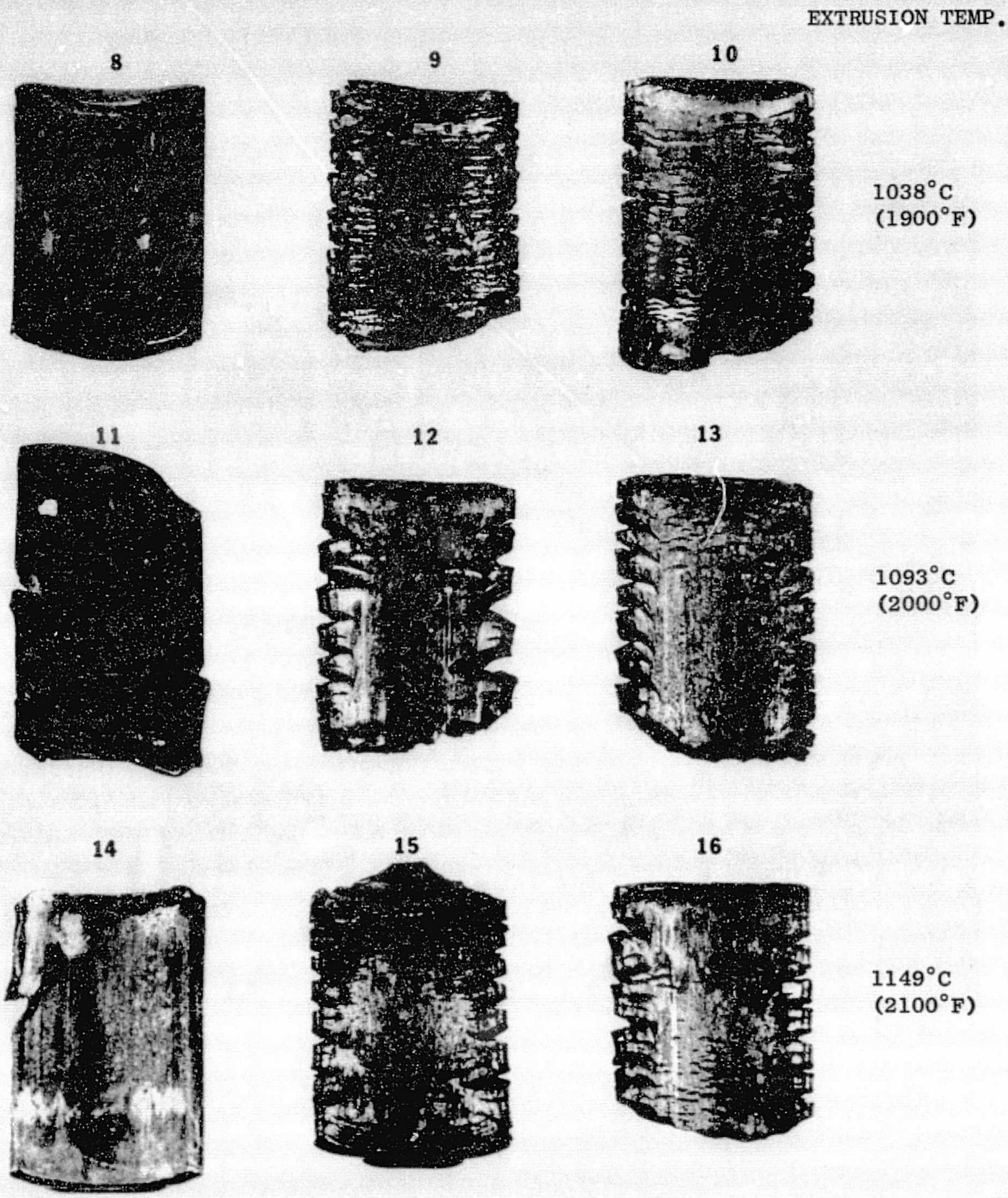
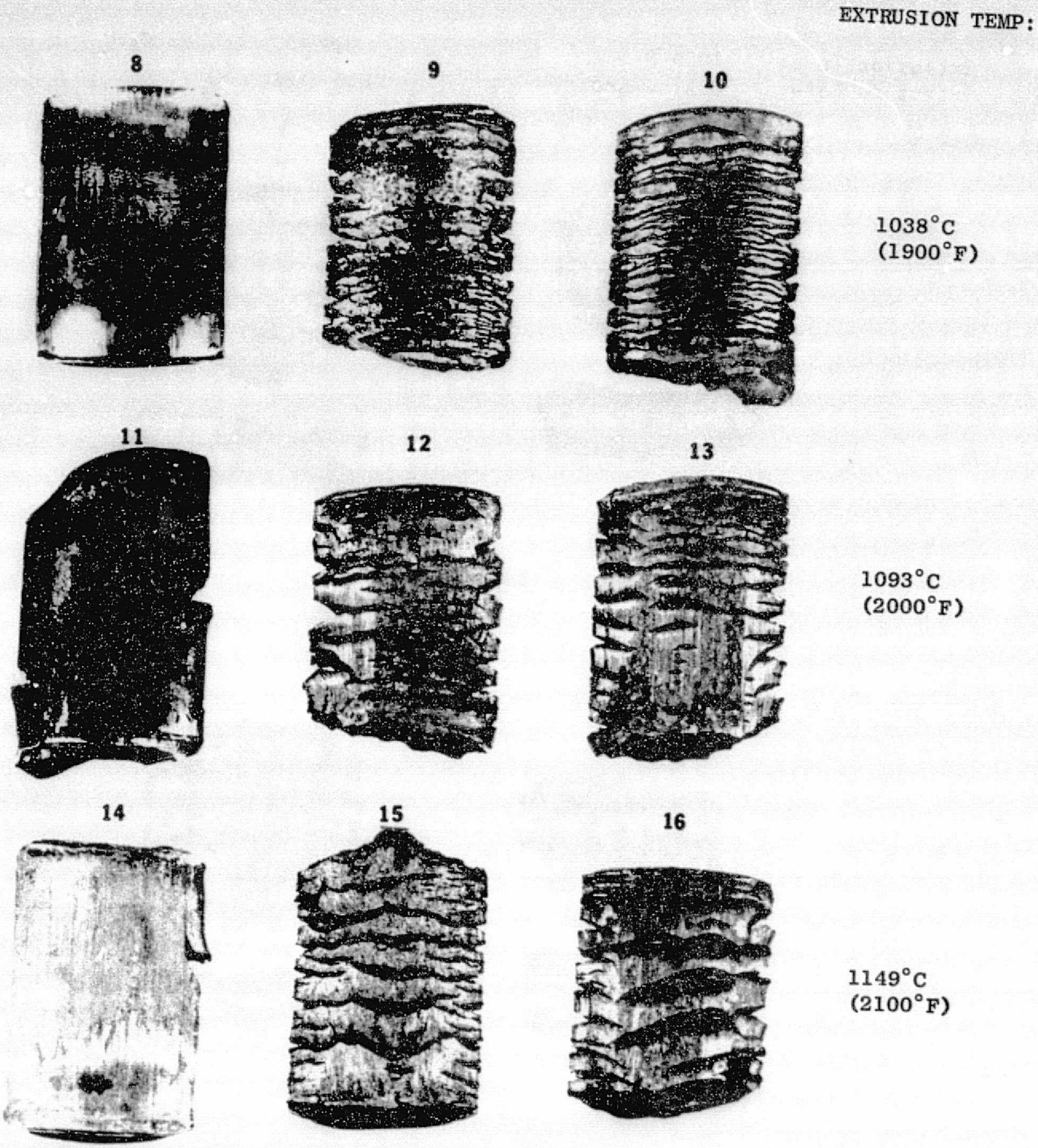


Figure 9. ODS Extrusion Tooling Installed in a 150-Ton Hydraulic Press



(a) CONCAVE SIDE ODS EXTRUSIONS NOS. 8, 11 AND 14 ARE ODS FeCrAl AND 9, 10, 12, 13, 15 AND 16 ARE ODS NiCrAl.

Figure 10 ODS Alloy Extrusions - 0.7X

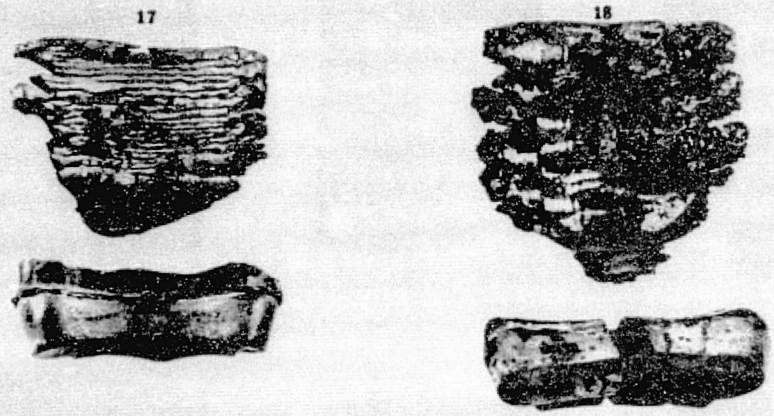


(b) CONVEX SIDE

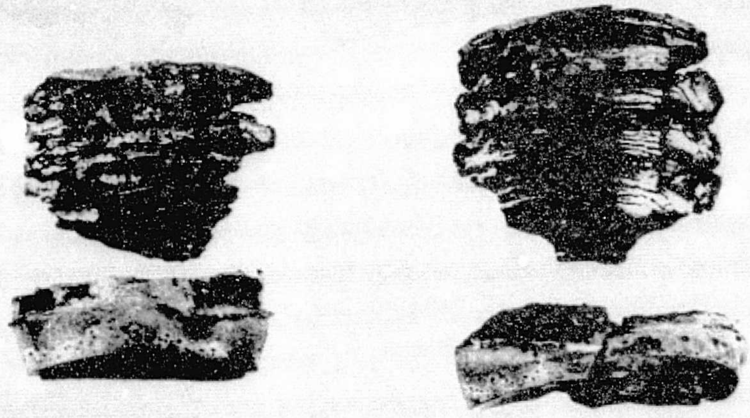
Figure 10 (Continued)

:xtrusion Temp: $1900^{\circ}F$
:xtrusion Rate: 0.2in./sec

5MM (0.2 IN.)/SEC.
1149°C(2100°F)



CONCAVE SIDE



CONVEX SIDE

(c) ODS NiCrAl MATERIAL EXTRUDED AT LOW EXTRUSION RATES

Figure 10 (Continued)

Tooling and Equipment Design

Directional forging tooling was designed and built from an AISI H-13 tool steel having higher carbon and vanadium contents for improved wear resistance and good toughness. The designs for the forge tooling are shown in Figure 11. The tooling was designed for use in mechanical presses. Lateral flow was prevented by the design of a closed die system in which the die sidewalls and the clearances between the upper punch and die wall prevent flashing. It is assumed the starting preform is of the same width (allowing for expansion) as the die cavity width. The machined and heat treated tooling is shown in Figure 12.

Experimental Procedure and Results

Design of the Campaign I forging trials with HDA 8077 and MA 956 alloys was strongly influenced by the poor results of the extrusion trials. Emphasis was placed on minimizing the heat loss from the workpiece to the warm about 204°C (400°F) tooling and on improving lubrication. Forging was performed in a longitudinal direction as indicated in Table III. The preforms as prepared for forging are shown in Figure 13. Twenty-one kidney shaped preforms, 12.7 mm (0.5 inches) thick x 55.9 mm (2.2 inches) are length x 43.2 mm (1.7 inches) long were forged at 1038°C (1900°F) to a 60% thickness reduction (three 25% reductions). These forgings are shown in Figure 14. Preform conditions investigated were bare, wrapped in clad (TD Ni, steel) or nickel plate. Some preforms were recrystallized prior to the secondary working. The elapsed time from the furnace through forging was only four to five seconds. The upset rate was very rapid, approaching that of a hammer process. Samples were taken at various steps of the processing to determine the effect of reduction level on the microstructure with a subsequent recrystallization heat treatment. The results were very promising and dramatically better than those of the extrusion process. The results of the HDA 8077 Campaign I forging experiments are:

(1) The HDA 8077 extruded "gullwing" material was greatly improved by directionally forging. The primary extruded material was insufficiently processed to obtain the (001) textured microstructure subsequent a recrystallization heat treatment. The central region contained a dual crystallographic orientation. This region was distinguishable by the highly reflective grains which composed about half of the central area as shown in Figure 6. Forgings Nos. 6, 13 through 19 and 21 after heat treating and macroetching exhibited the desirable grain size, shape and crystallographic orientation. The microstructures of the other forgings were much improved but still contained grains of higher modulus orientation.

(2) Forgings Nos. 13, 14 and 15 came from preform materials which had seen different amounts of primary work but did cause an effect on forgeability.

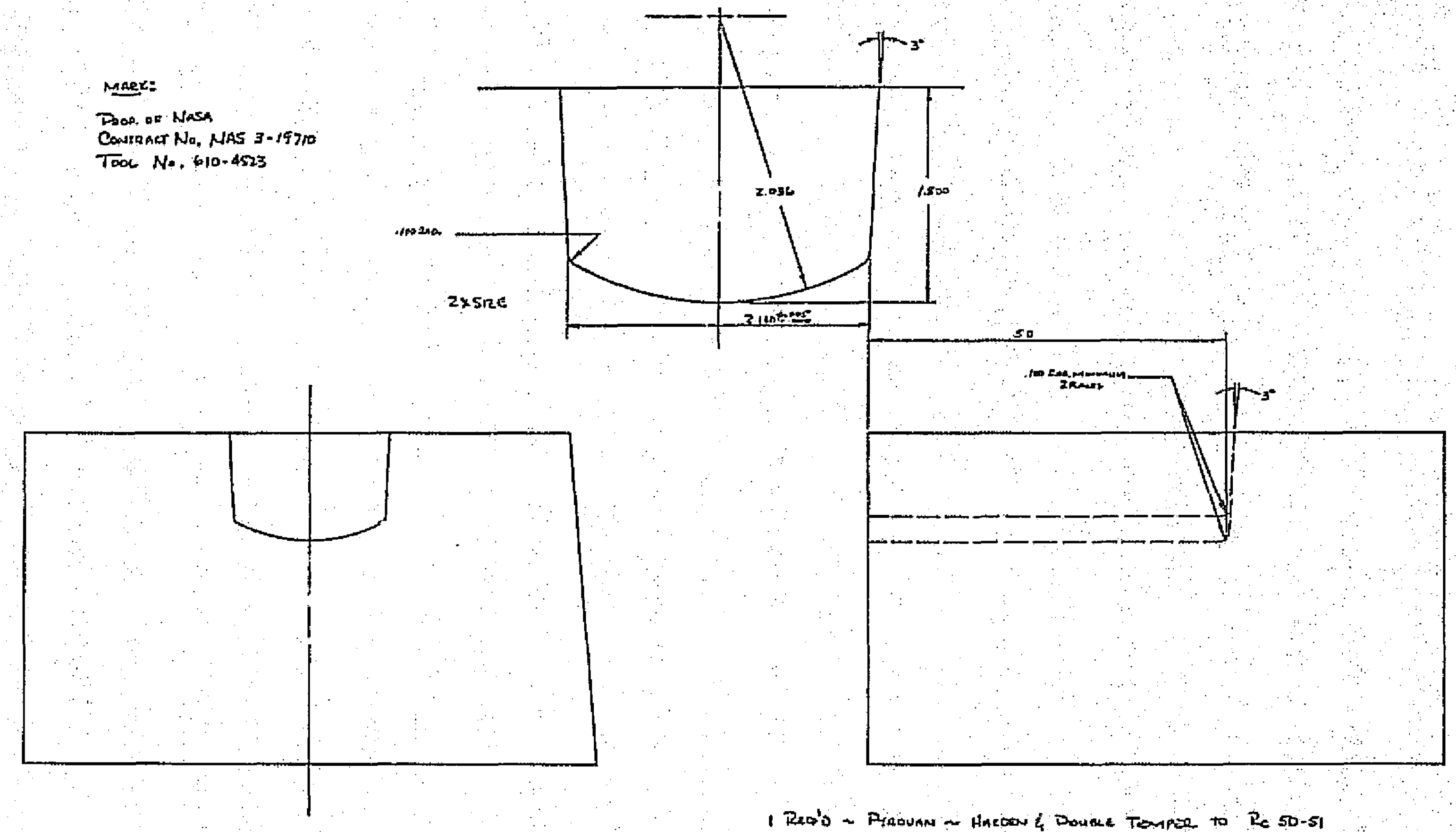
(3) Oxide dispersion content has a noticeable affect on forgeability. Comparing No. 20 forged 70% (because of the increased preform thickness) in one 47% and two 25% reductions and No. 21 reduced 45% in one reduction, indicates that higher forging reductions are unacceptable for the high

TABLE III. DIRECTIONAL FORGINGS - CAMPAIGN I - 1038°C (1900°F)

S/N	MATERIAL	GULLWING EXTR. NO.	DISPERSOID CONTENT %	PREFORM PREPARATION	PERCENT REDUCTION	APPEARANCE	MICROSTRUCTURE
1	HDA 8077	4	1.3	Bare + Glass	60	Slight Edge Cracking	Improved (1)
2	HDA 8077	4	1.3	Bare + Glass	60	Slight Edge Cracking	Improved
3	HDA 8077	4	1.3	Ni Plate + Glass	60	Slight Edge Cracking	Improved
4	HDA 8077	4	1.3	Ni Plate + Glass	60	Slight Edge Cracking	Improved
5	HDA 8077	4	1.3	SS Clad + Glass	40	No Cracks	Improved
6	HDA 8077	4	1.3	TDNi Clad + Glass	60	No Cracks	Good (2)
7	HDA 8077	4	1.3	Rx'd + Glass	60	Slight Edge Cracking	Improved
8	HDA 8077	4	1.3	Rx'd + Glass	60	No Cracks	Improved
9	HDA 8077	4	1.3	Bare	60	Slight Surface and Edge Cracking	Improved
10	HDA 8077	4	1.3	Bare	50	Slight Edge Cracking	
11	MA956	5	---	Bare + Glass	60	No Cracks	---
12	MA956	5	---	TDNi Clad + Glass	25	No Cracks	---
13	HDA 8077	1	1.8	Bare + Glass	60	Surface and Edge Cracking	Good
14	HDA 8077	2	1.8	Bare + Glass	60	Surface and Edge Cracking	Good
15	HDA 8077	3	1.8	Bare + Glass	60	Surface and Edge Cracking	Good
16	HDA 8077	3	1.8	Ni Plate + Glass	60	Slight Edge Cracking	Good
17	HDA 8077	3	1.8	TDNi Clad + Glass	45	No Cracks	Good
18	HDA 8077	3	1.8	Rx'd + Glass	60	Slight Edge Cracking	Good
19	HDA 8077	3	1.8	Bare	25	Slight Edge Cracking	Good
20	HDA 8077	-	0.6	Bare + Glass	70	Slight Edge Cracking	Fair
21	HDA 8077	2	1.8	Bare + Glass	45	Severe Cracking	Good

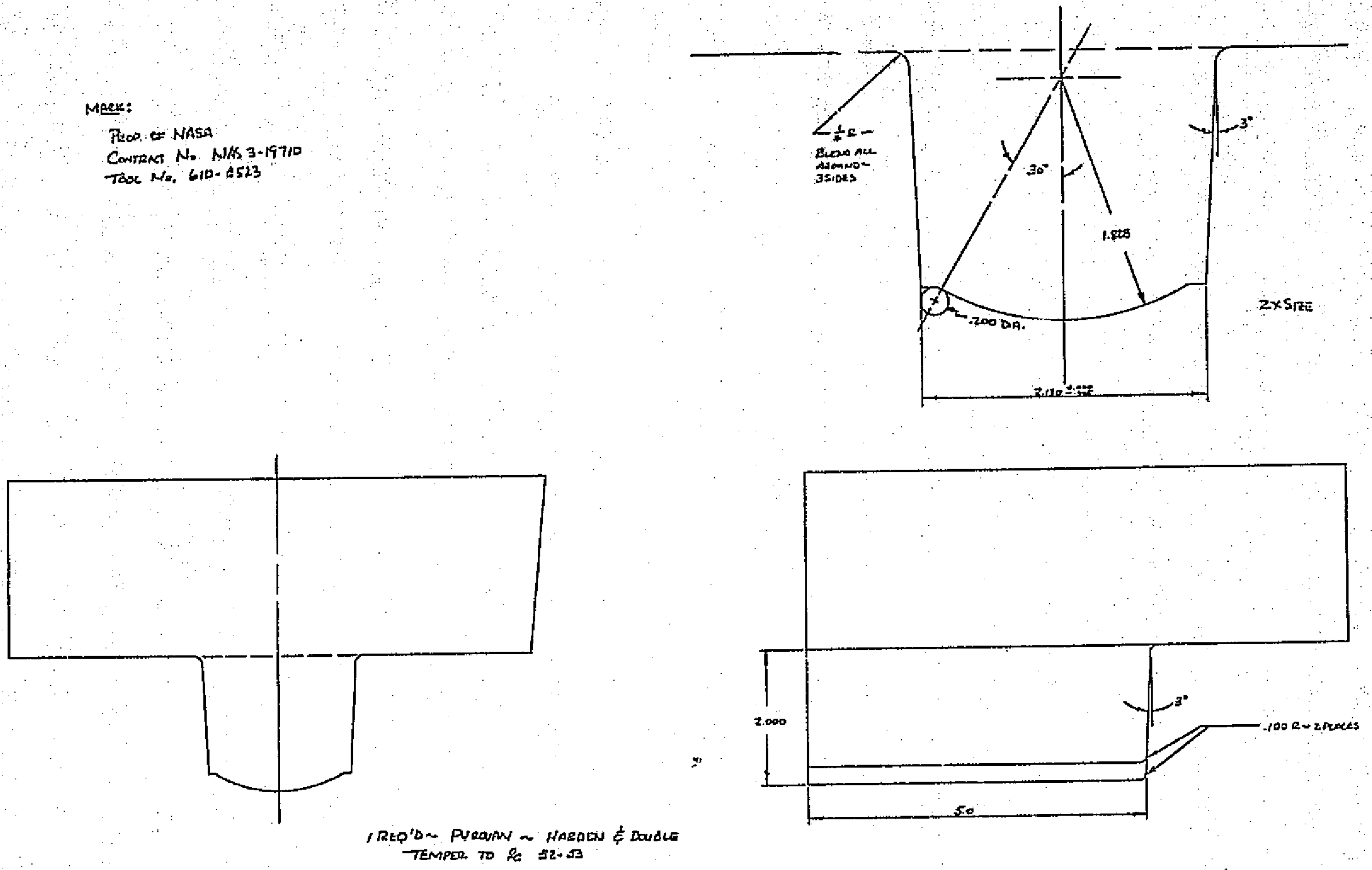
(1) Improved by forging, but still contained grains of exceedingly high 172 MPa (25×10^6 PSI) modulus values in the longitudinal direction.

(2) Good grain size, shape and crystallographic orientation (nearly (001).



(b) DIE

Figure 11 ODS Alloy Directional Forging Tooling Design



(a) PUNCH

Figure 11 (Continued)

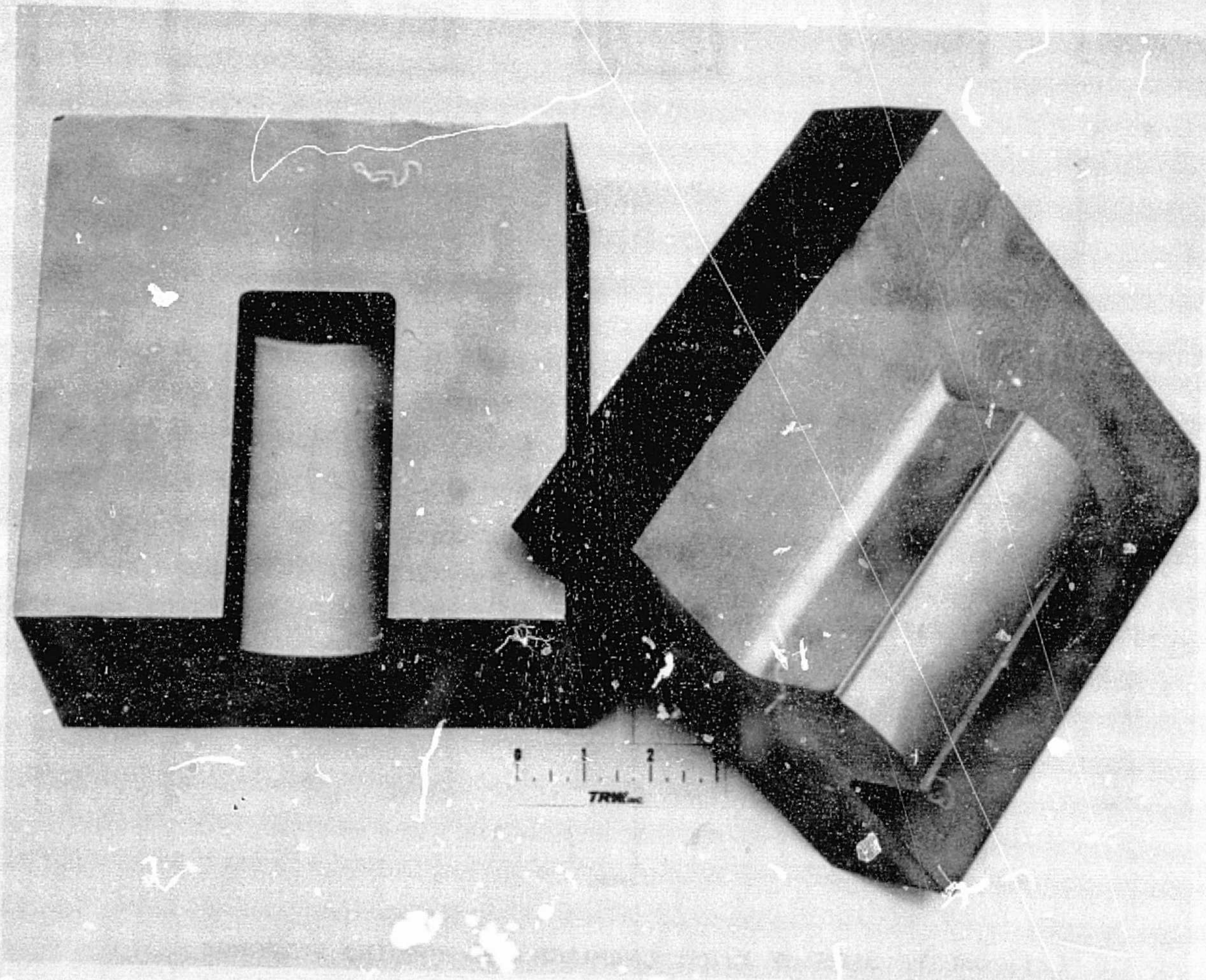
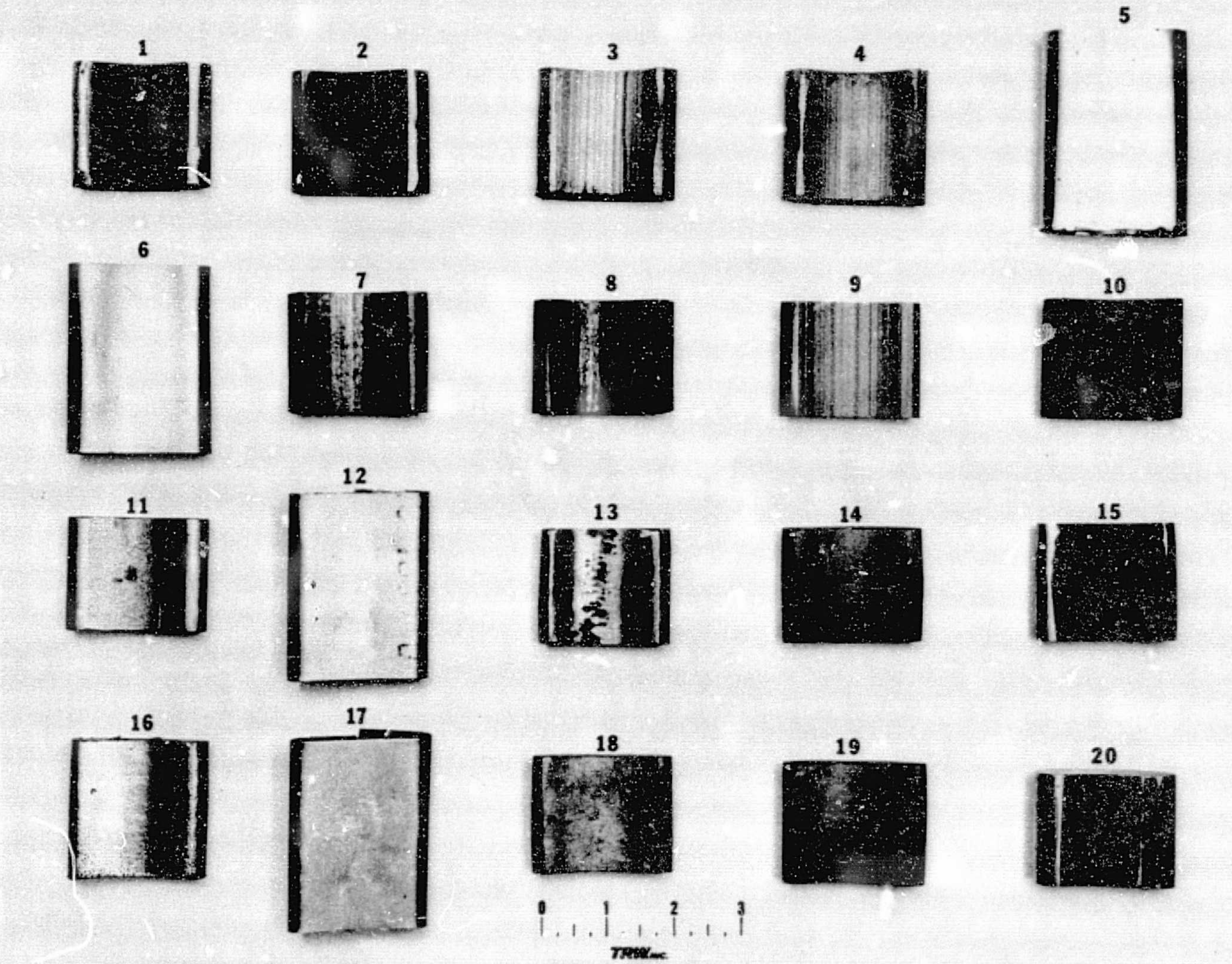
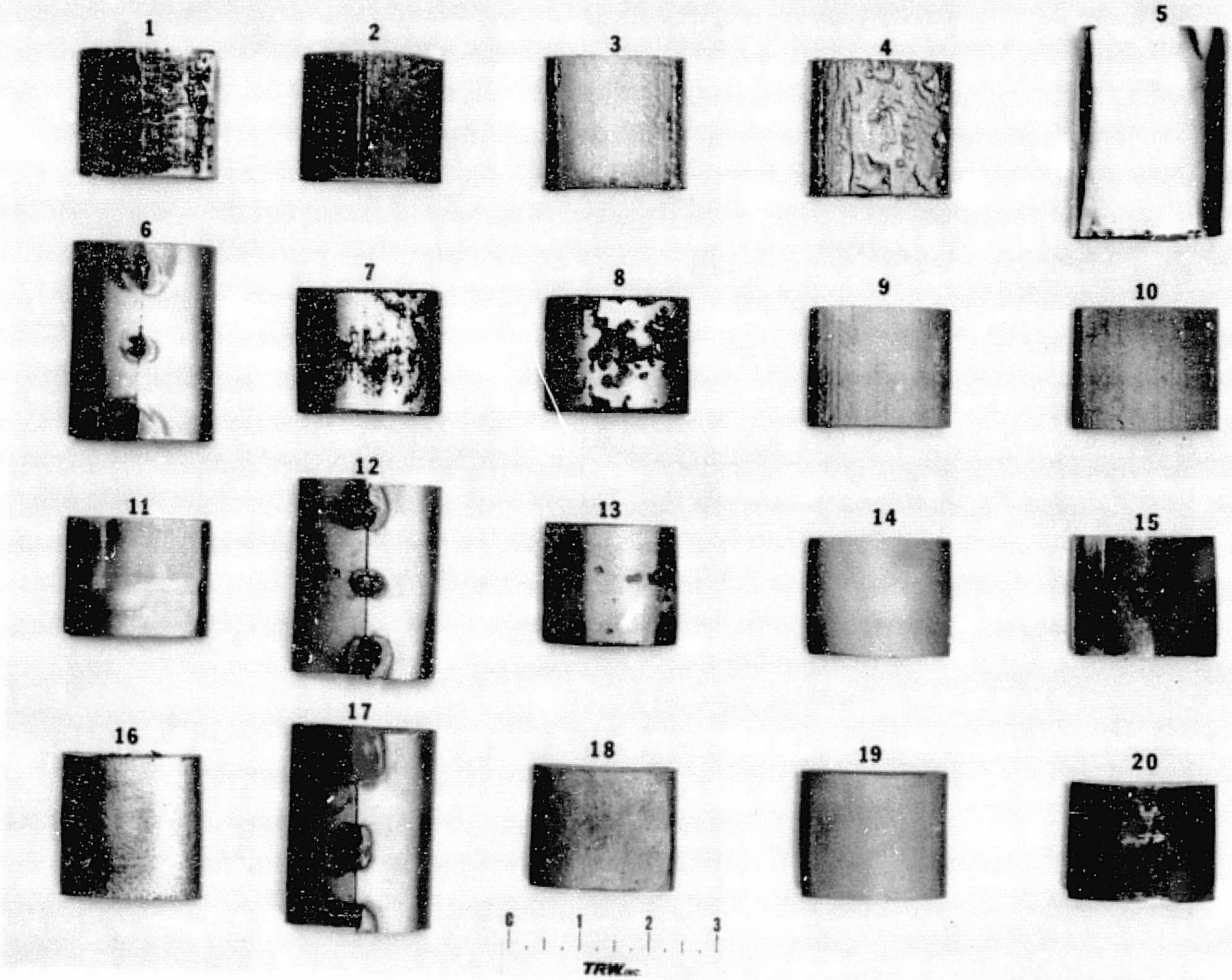


Figure 12. ODS Alloy Vane Directional Forging Tooling



(a) CONCAVE SIDE OF FIRST CAMPAIGN ODS FORGING PREFORMS.

Figure 13 ODS Alloy Forging Preforms



(b) CONVEX SIDE OF FIRST COMPAIGN ODS FORGING PREFORMS.

Figure 13 (Continued)

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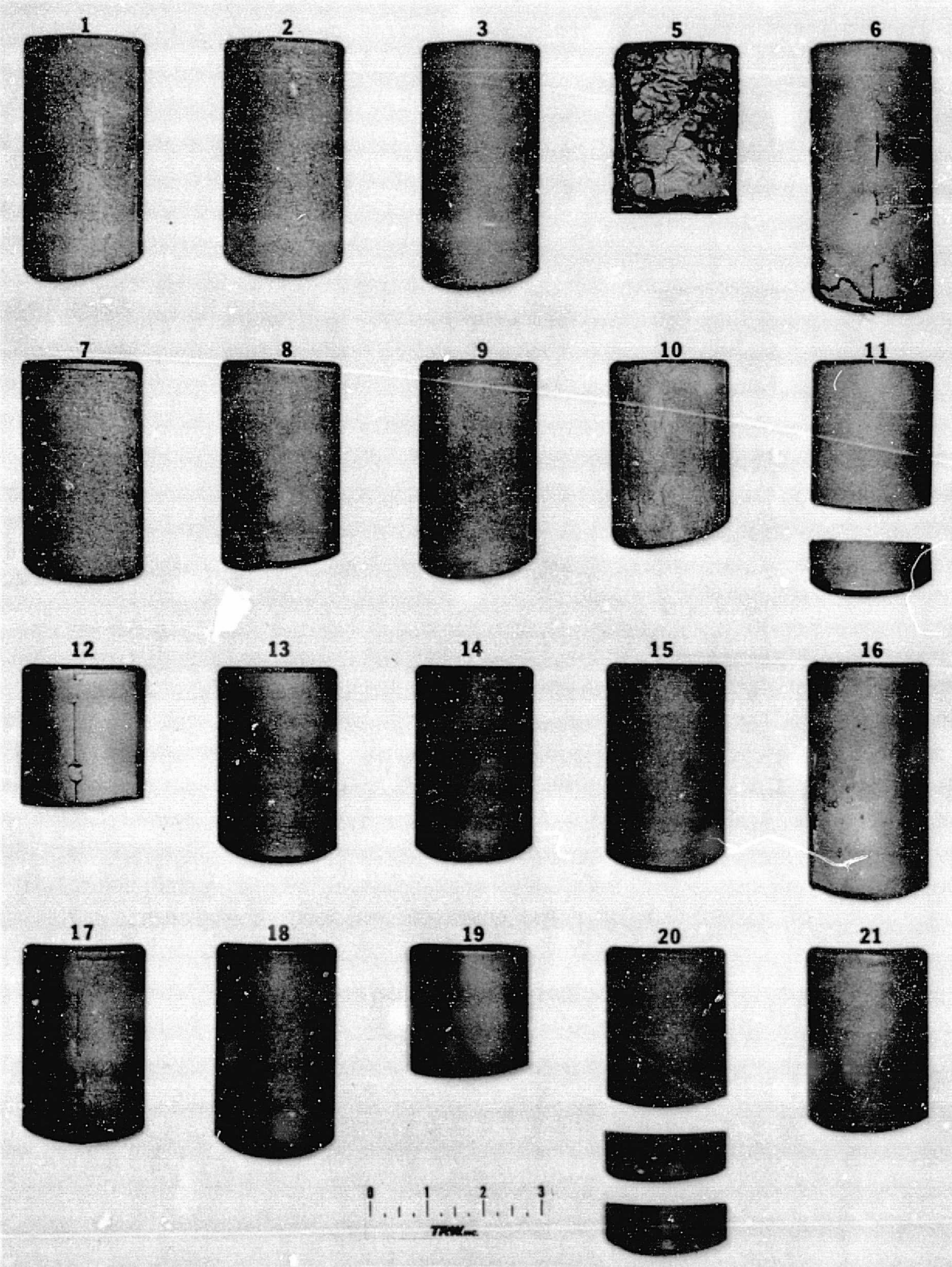
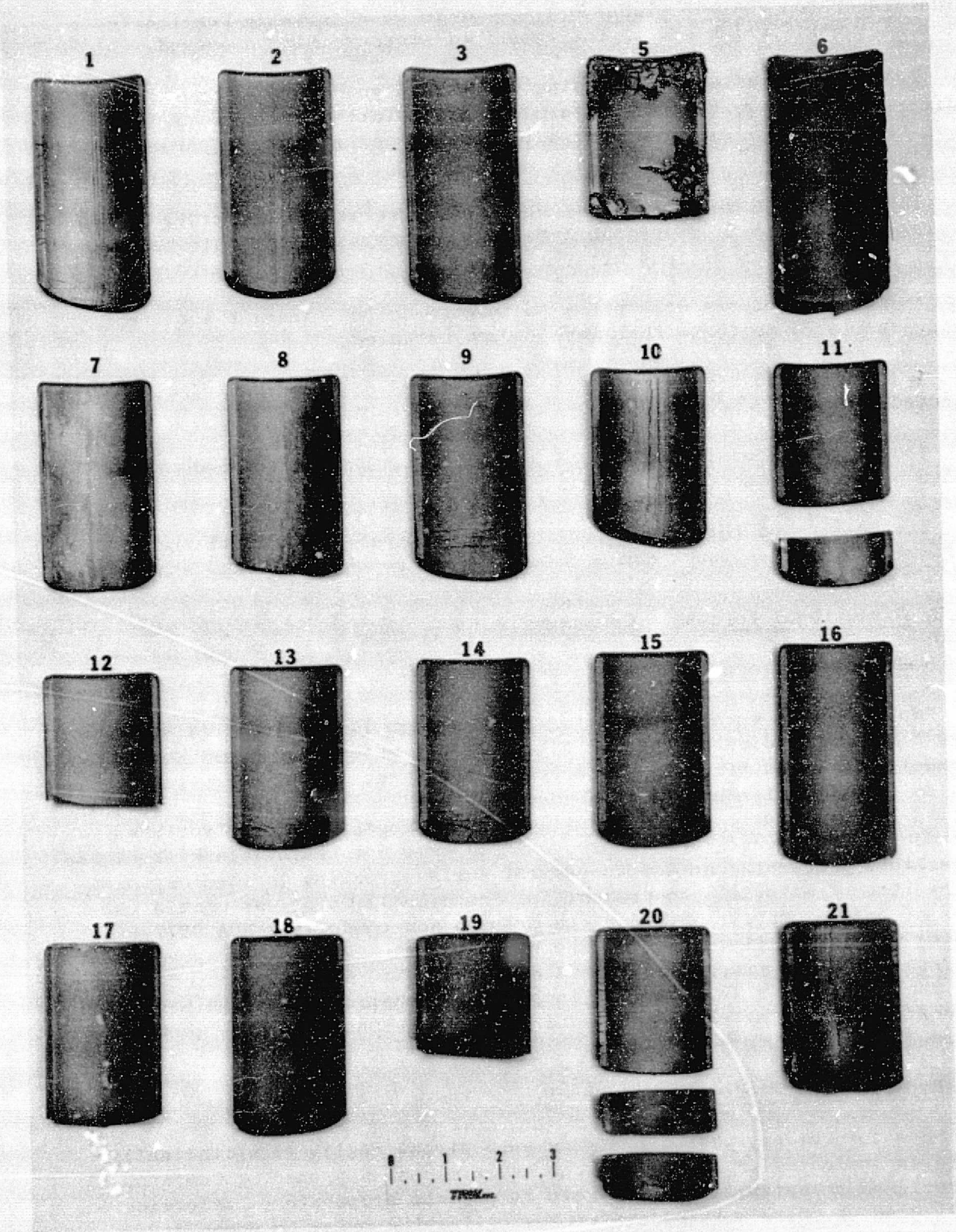


(a) CONCAVE SIDE

Figure 14 Directionally Forged Campaign I ODS Alloy NNS Canning Material Not Removed.



(b) CONVEX SIDE OF FIRST CAMPAIGN FORGING TRAILS

Figure 14 (Continued)

oxide dispersion content (1.8%) but appear to be acceptable for the low oxide content (0.6%) based on the amount of edge cracking observed.

(4) Nickel plating and cladding with sheet such as TDNi appeared to minimize the surface tearing. Stainless steel foil clads such as that used for forging #5 ruptured during processing and eventually caused sticking of the foil to the die.

(5) Preforms Nos. 7, 8 and 18 which were recrystallized prior to forging exhibited better forgeability than unrecrystallized material and excellent surface conditions after forging.

(6) Coating of preforms prior to forging helped minimize surface tearing compared to those that were forged uncoated.

(7) The MA 956 demonstrated excellent forgeability. No cracks were detected.

(8) Forge processing of MA 956 at 1900°F to 25% and 60% reductions failed to produce the (001) orientation.

The results of this first forging campaign have shown that the directional forging approach can be used to produce near-net vane shapes.

2.4.3 Directional Forging - Campaign II

Selected Alloys and Configurations

New materials were procured for the Campaign II forging trials. Campaign I results indicated the ODS alloy preform materials should be optimumly processed prior to NNS forging, i.e., capable of recrystallization to the (001) texture in a subsequent anneal heat treatment. The lower forging temperatures required to tailor under processed microstructures by inducing additional work (stored energy) were not compatible with higher temperature processing needed to prevent surface tearing in the forgings. At the time of material procurement for Campaign II Cabot was unable (because of an inoperative attritor) to prepare new powder for HDA 8077 extrusion within the time frame of the program. MA 757 which is very similar in preparation and properties to HDA 8077 and YDNiCrAl was procured in 30.5 mm (1.2 inches) thick x 76.2 mm (3.0 inches) wide shaped bar. This as-rolled (unrecrystallized) material was machined to the kidney shape as shown in Figure 15.

Experimental Procedure and Results

Seventeen kidney shaped preforms were directionally (longitudinally) forged as indicated in Table IV. The experimental approach of Campaign II was designed to establish the effects of process temperature, reduction level, clad vs. bare working and recrystallization prior to secondary working to NNS. The as-forged parts are shown in Figure 16 and with the claddings removed and grit blasted in Figure 17.

Seven MA 757 preforms were forged at 1038°C (1900°F) and 1093°C (2000°F) to reductions of 25% and 50%. Most of the preforms were wrapped in 1.27 mm (.050 inches) thick mild steel. One MA 757 preform, F11, was processed unclad. One preform, F8, was recrystallized prior to secondary processing.

TABLE IV - TASK I CAMPAIGN II DIRECTIONAL KIDNEY FORGING PARAMETERS

S/N	ODS Alloy	Preparation	Conversion Temp.[1] °C (°F)/Red., %	Appearance: Surface Tearing[2]	Appearance: Undulation[3]	Appearance: Macrostructure
F2	MA 757	clad[4]	1038 (1900)/25	very slight	slight	good
F4A	MA 757	clad	1038 (1900)/50	moderate	moderate	good
F4B	MA 757	clad	1038 (1900)/50	moderate	moderate	good
F8	MA 757	Rx + clad	1038 (1900)/50	none	slight/moderate	good
F11	MA 757	unclad	1093 (2000)/50	moderate	none	marginal
F14	MA 757	clad	1093 (2000)/50	moderate	gross	good
F15	MA 757	clad	1093 (2000)/50	moderate	gross	good
F5	YD NiCrAl	clad	1038 (1900)/25	very slight	slight	poor
F7A	YD NiCrAl	clad	1038 (1900)/50	slight	moderate	poor
F7B	YD NiCrAl	clad	1038 (1900)/50	slight	moderate	poor
F10	YD NiCrAl	Rx + clad	1038 (1900)/50	none	slight	good
F12	YD NiCrAl	unclad	1093 (2000)/50	slight (edge)	none	poor
F16	YD NiCrAl	clad	1093 (2000)/25	none	slight	fair
F17	YD NiCrAl	clad	1093 (2000)/50	slight	gross	duplex
F18	YD NiCrAl	clad	1093 (2000)/50	slight	gross	duplex
F1	MA 956	unclad	982 (1800)/50	none	none	poor
F13	MA 956	unclad	1093 (2000)/50	none	none	poor

(1) Kidney Forging, 25% reduction per pass.

(2) Defect depth: moderate = < 1.27 mm (.050"); slight = < .254 mm (.010").

(3) Undulation depth: gross = < 2.54 mm (.1"); moderate = < .51 mm (.02"); slight = < .254 mm (.01").

(4) Clad: 1.27 mm (.050") mild steel wrap.

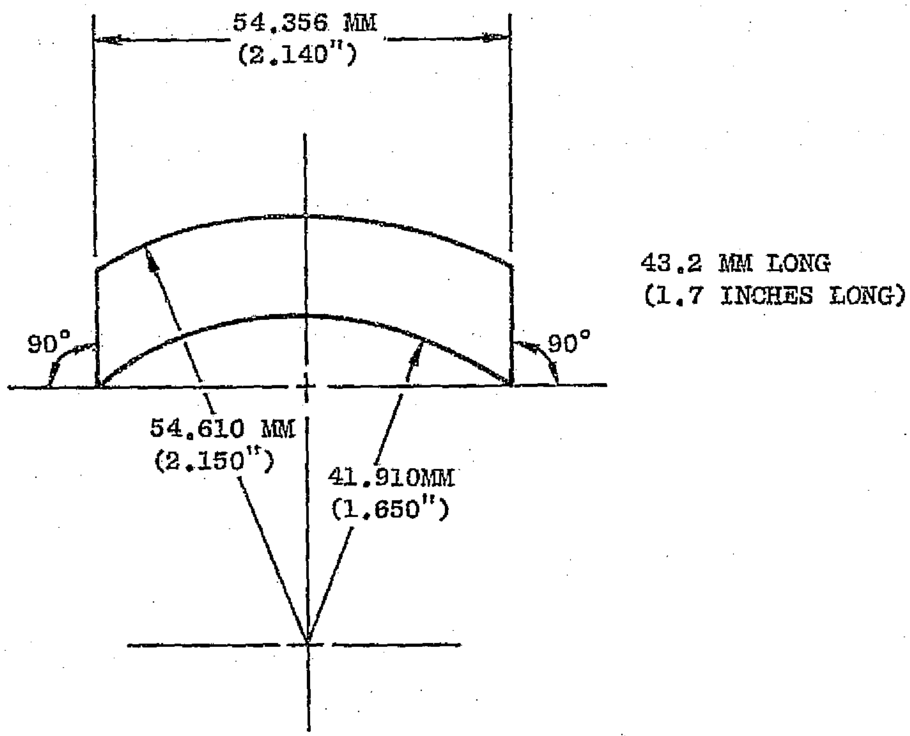
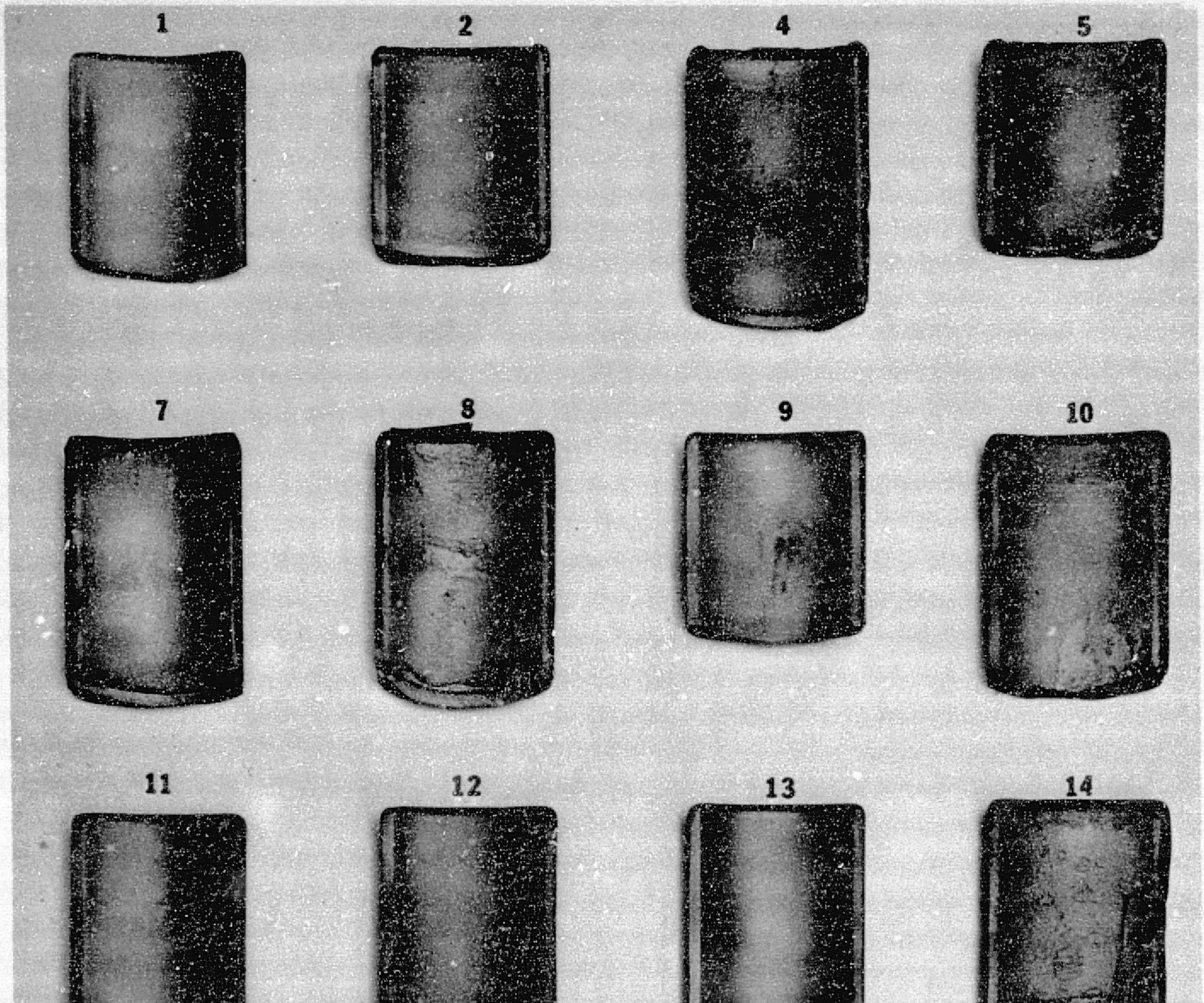
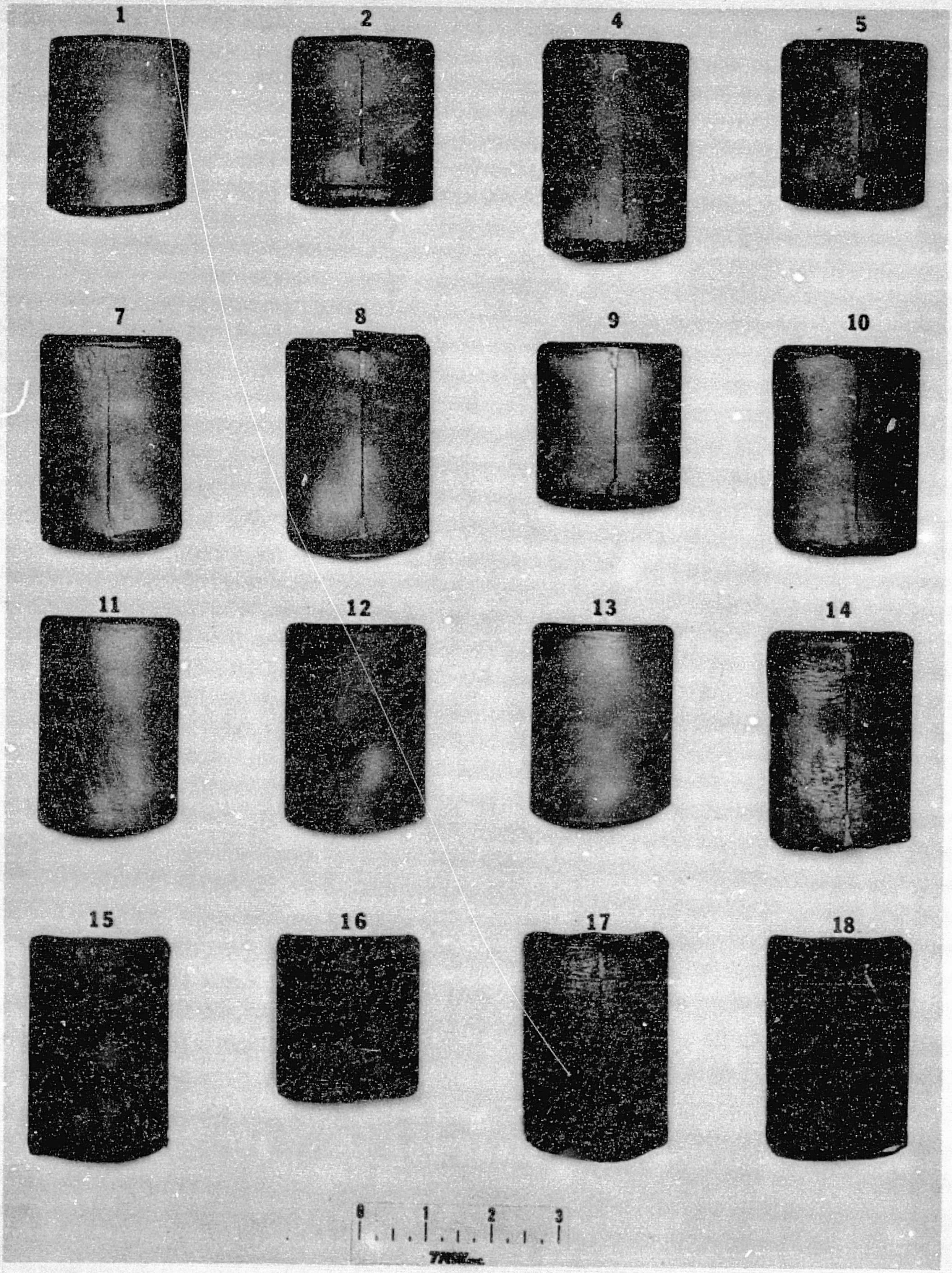


Figure 15 Machined Kidney Shaped Preform Design

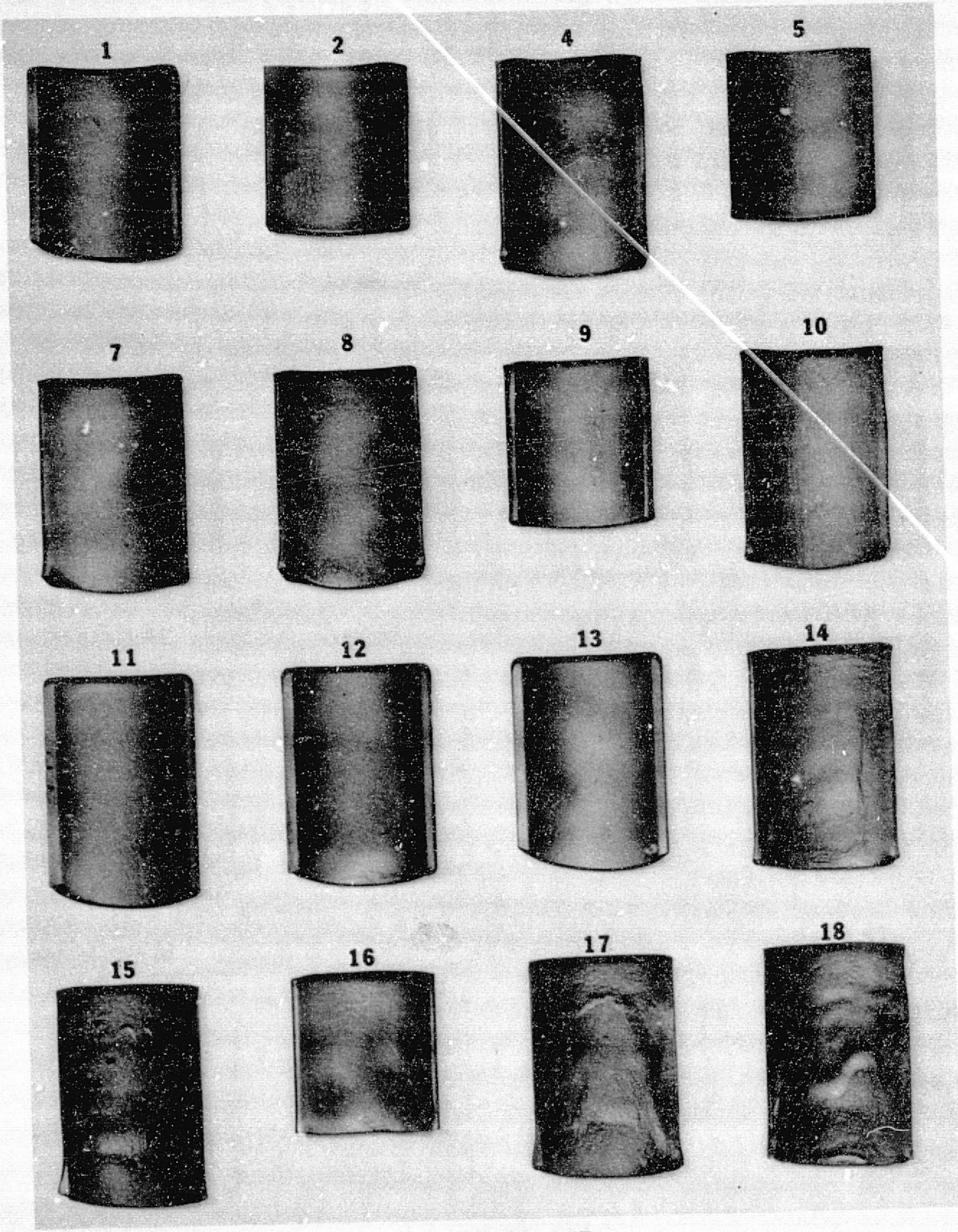


(a) CONCAVE SIDE

Figure 16 Directionally Forged Campaign II NNS Canning Material Not Removed

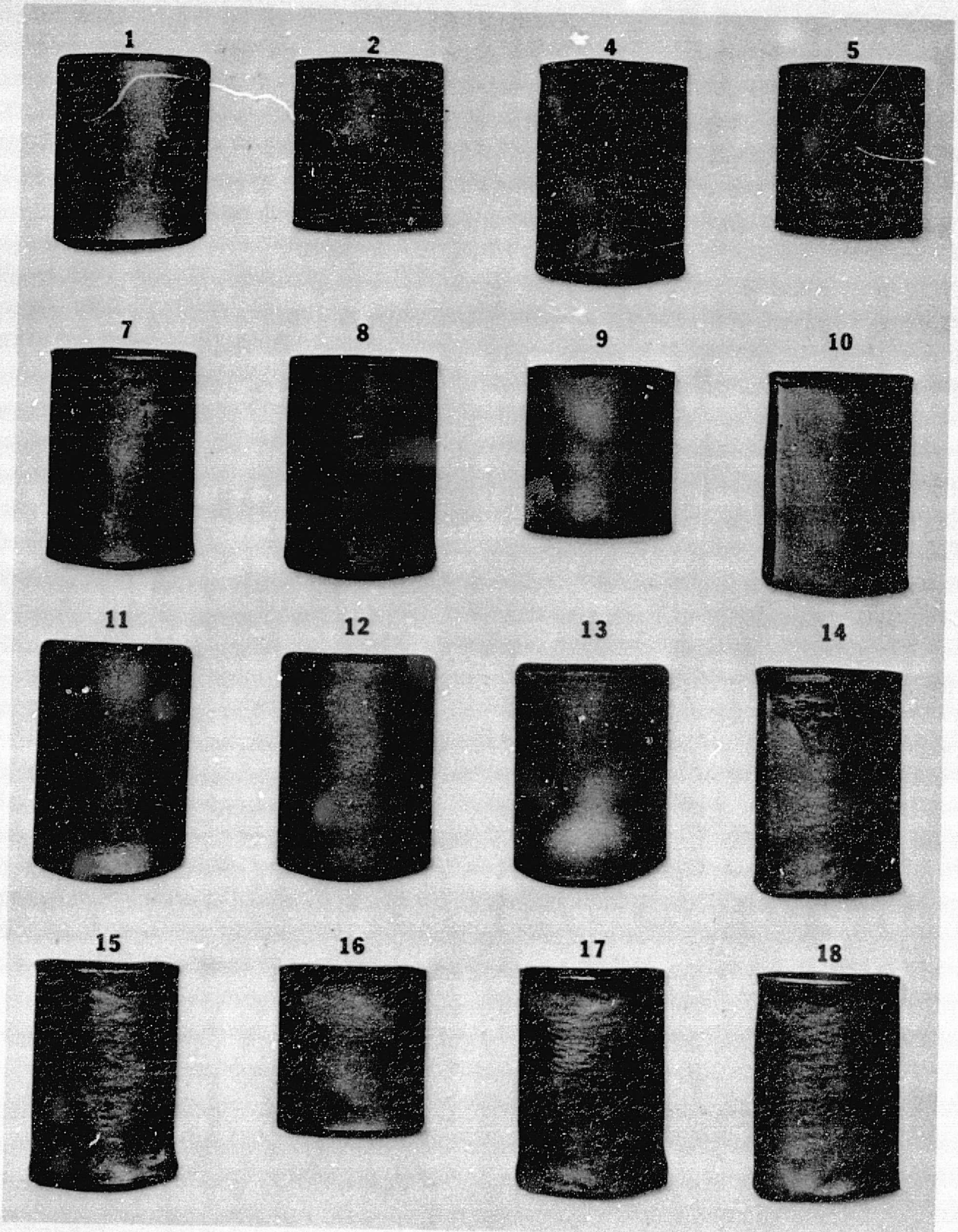


(b) CONVEX SIDE OF CAMPAIGN II FORGING TRAILS.
Figure 16 (Continued)



(a) CONCAVE SIDE.

Figure 17 Directionally Forged Campaign II NNS Canning Material Removed



(b) CONVEX SIDE
Figure 17 (Continued)

The desired microstructure was achieved in all the forgings by subsequent recrystallization heat treatment except in the unclad F11. Heat treating was performed using a progressive temperature cycle - 1205°C (2200°F), 1260°C (2300°F) and 1315°C (2400°F) for one hour each temperature. Macro-etched cross-sections representative of all the MA 757 forge conditions investigated are shown in Figure 18. All exhibit the desirable (001) textured structure except for S.N. F11 which contained regions of higher modulus orientations indicated by their light reflectivity. The mild steel clad performed satisfactorily at 1900°F in reductions up to 50% but produced excessive surface undulations at 2000°F in 50% reductions. Some surface tearing was experienced in all the MA 757 forgings with the exception of the recrystallized and clad F8. Generally, the surface defects ranged from .254 mm (.01 inches) to 1.27 mm (.05 inches) deep. The unclad MA 757 preform, F11, processed at 1093°C (2000°F) to 50% reduction had no undulation but contained surface tears about 1.27 mm (.05 inch) deep and a marginal texture on recrystallization. The recrystallized MA 757 preform, F8, wrapped in steel clad and forged at 1038°C (1900°F) to a 50% reduction forged well without cracking or surface defects. This forging was exposed to a 1315°C (2400°F) heat treatment and evaluated for microstructural stability. The additional processing during forging of the recrystallized material did not promote re-recrystallization or degradation of the (001) texture.

Eight YDNiCrAl kidney shaped preforms were processed and the results were somewhat different than for the MA 757 material. The secondary working conditions investigated promoted an unacceptable fine grained material with random crystallographic orientation after the recrystallization heat treatment. The more ductile YDNiCrAl has better crack resistance than the longitudinally stronger but less ductile MA 757. The unclad YDNiCrAl preform, F12, forged at 1093°C (2000°F) to 50% reduction contained only minor cracking on the sharp edges, indicating higher temperatures would probably allow bare working, especially if recrystallized prior to the secondary working. The recrystallized YDNiCrAl preform, F10, produced the same favorable results (See Figure 19) as achieved in the recrystallized MA 757 alloy. The texture was preserved, cracking was eliminated and no recrystallization was detected in a post forge 1315°C (2400°F) heat treatment.

Two MA 956 kidney preforms were included in this campaign. Both were processed unclad to 50% reductions, one at 982°C (1800°F) and the other at 1093°C (2000°F). Although forgeability was excellent the desired (001) microstructure was not obtained. Macrostructure typical of MA 956 forged kidneys in the recrystallized condition is also shown in Figure 19.

2.4.4 Plate Bending Process

An additional process, plate bending, was investigated in Campaign II. The basic approach is illustrated in Figure 20. The bent plate process is capable of producing the same shape as the forged kidney process, is a simple forming operation with no reduction in thickness and is amenable to all ODS alloys and vendors. The ODS alloy and plate bending parameters investigated are indicated in Table V. Hot rolled plate sections, approximately 7.37 mm (0.29 inches) thick x 53.3 mm (2.1 inches) wide x 81.3 mm

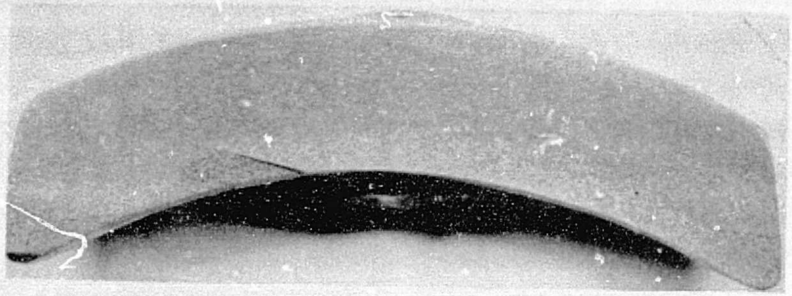
TABLE V - TASK I CAMPAIGN II PLATE BENDING(1) PARAMETERS

S/N	ODS Alloy	Preparation	Process Temp. °C	(°F)	Appearance: Cracking(2)	Recrystallized Macro Structures
B1	HDA 8077	clad	982	(1800)	Severe	Good(3)
B2	HDA 8077	unclad	1038	(1900)	Severe	Good
B3	HDA 8077	clad	1038	(1900)	None	Good
B4	HDA 8077	Rx + clad	1038	(1900)	Severe	Good
B5	HDA 8077	unclad	1093	(2000)	Slight	Good
B6	HDA 8077	clad	1093	(2000)	None	Good

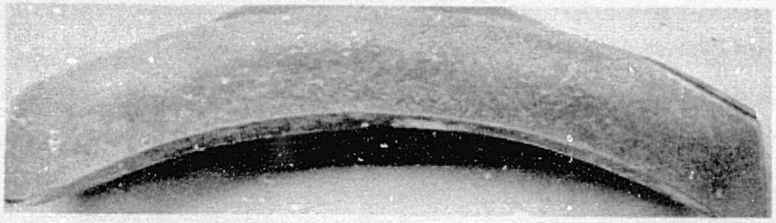
(1) Plate Bending: Formed to a 41.9 mm (1.65") Radius

(2) Cracking: Severe =>1.27 mm (.050"); Mode Rate =<.254 mm (.010")

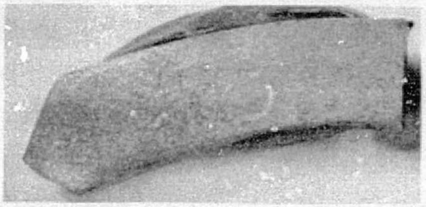
(3) Good grain size, shape and crystallographic orientation, nearly (001).



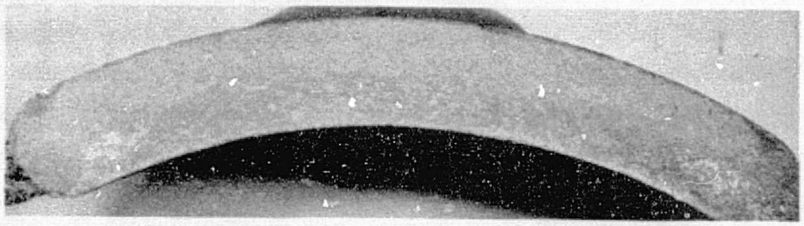
SN 2



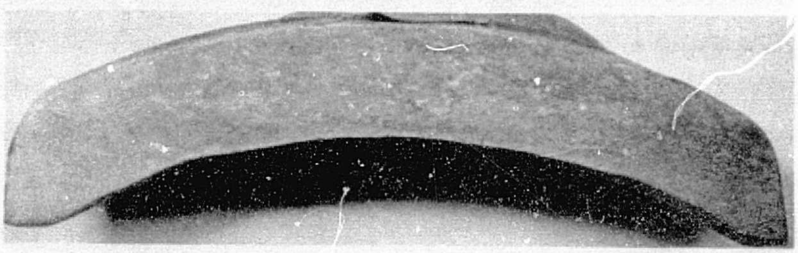
SN F4A



SN F8

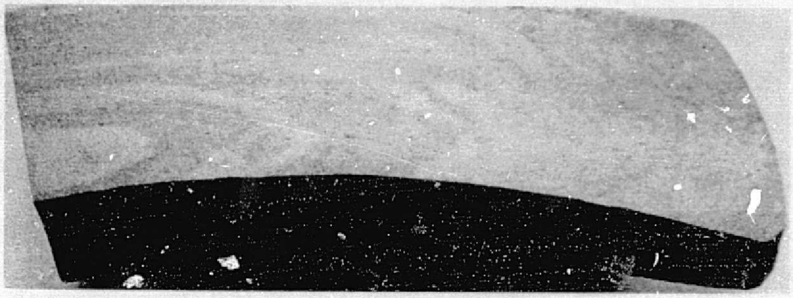


SN F11



SN F14

Figure 18 MA757 Directionally Forged Kidneys - Macroetched Cross-Sections



SN F10
(3X)

(a) YD NiCrAl

SN F13
(1.5X)

(b) MA956

Figure 19 Directionally Forged Kidneys

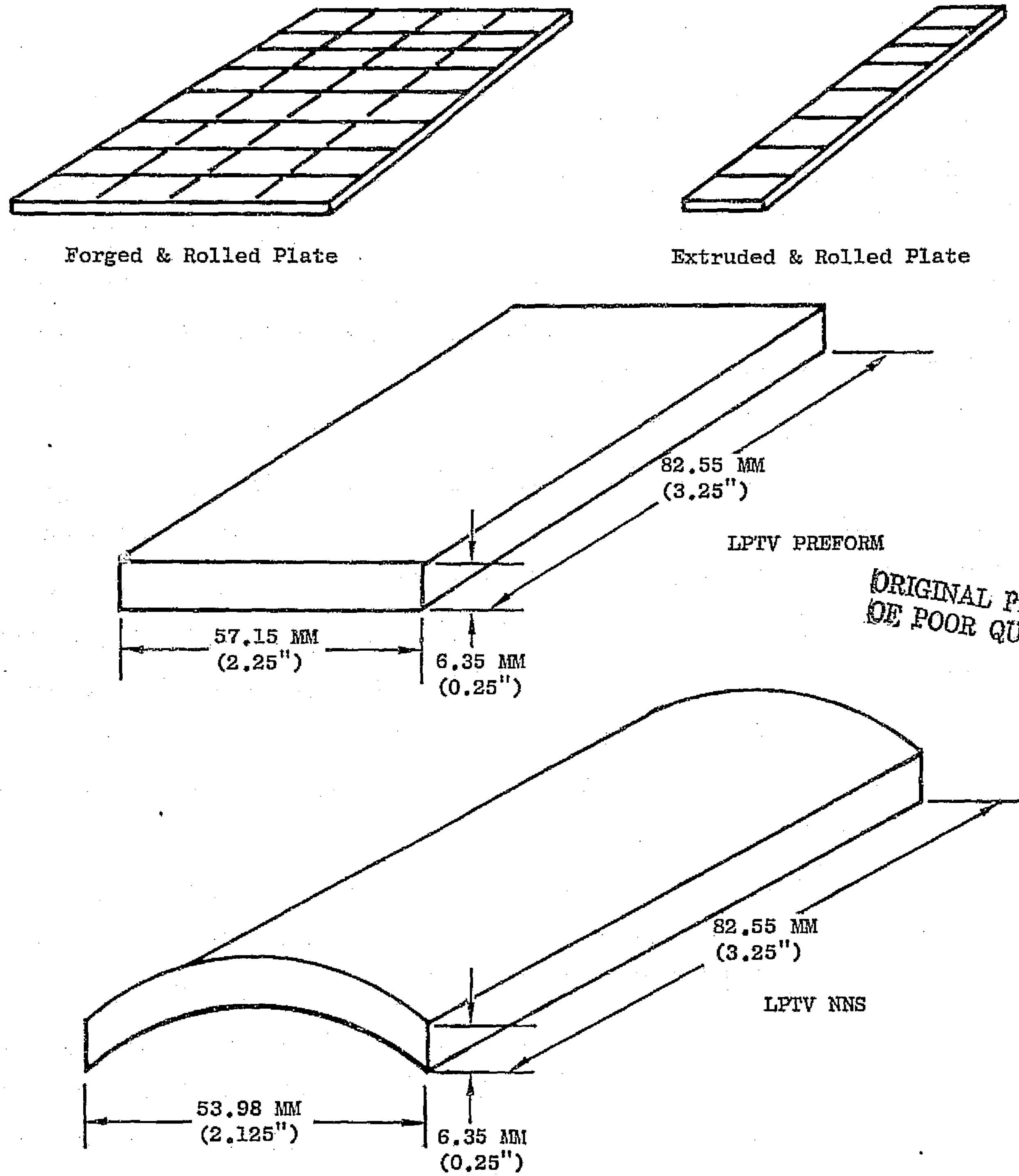


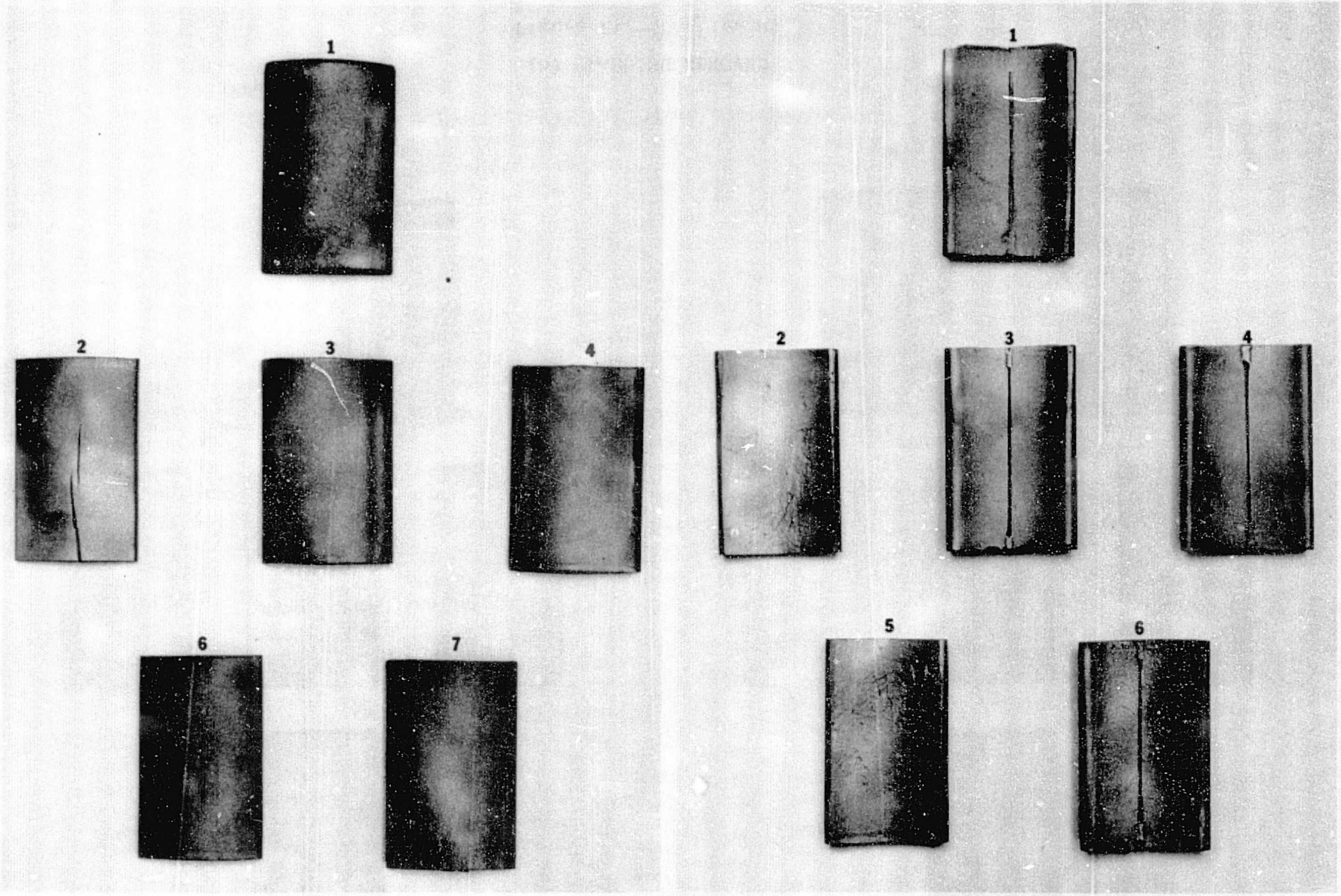
Figure 20 Plate Bending LPT Vane NNS Process

(3.2 inches) long were bent to a 41.9 mm (1.65 inch) radius in the same tooling used for the forge processing. Steel clad (wrapped) and unclad plates were bent at temperatures of 1800°F, 1900°F and 2000°F and are shown in Figure 21. Unclad preforms B2 and B5 were bent at 1900°F and 2000°F respectively. At 1900°F severe cracking, > 1.27 mm (0.05 inches) deep, was experienced but at 2000°F only slight, <.25 mm (0.01 inches) deep, cracking was detected. B1, B3 and B6 were wrapped in steel clad and bent at 1800°F, 1900°F and 2000°F. Severe cracking was encountered in B1 after bending at 1800°F. Simulated NNS B3 and B6 bent well without cracking. B4 recrystallized and wrapped in steel clad cracked severely during bending at 1900°F. Bending results in tensile stresses unlike forging in which strains are compressive. Recrystallizing ODS alloys substantially reduced the high temperature tensile ductility but, apparently, not the compressive ductility. All parts after bending and heat treating to 2400°F contained the desired structure.

Additional plate bending experiments were performed at General Electric, subsequent to the TRW Campaign II processing. The plate experiments performed in the directional forging tooling were formed to a 41.9 mm (1.65 inch) radius which is larger than a vane minimum radius. At General Electric 6.35 mm (0.25 inch) x 55.9 mm (2.2 inches) x 76.2 mm (3.0 inches) MA 757 extruded and rolled material, prepared from 30.5 mm (1.2 inch) thick bar stock, was successfully bent at 1093°C (2000°F) and 1149°C (2100°F) to 25.4 mm (1.0 inch) and 12.7 mm (0.5 inch) radii. The LPT vane has a minimum radius of 25.4 mm (1.0 inches). Either mild steel clad or fiber frax insulation were used. Bare processing was not attempted because of an insufficient number of parts for evaluation. Recrystallization anneal and metallographic examination indicated the desired structure and texture were maintained in bending as typically shown in Figure 22. The plates bent to the 12.7 mm (0.5 inch) radius showed the relatively large tolerance of the material when starting with an optimumly processed preform condition.

2.4.5 Evaluation of Simulated Near Net Shapes

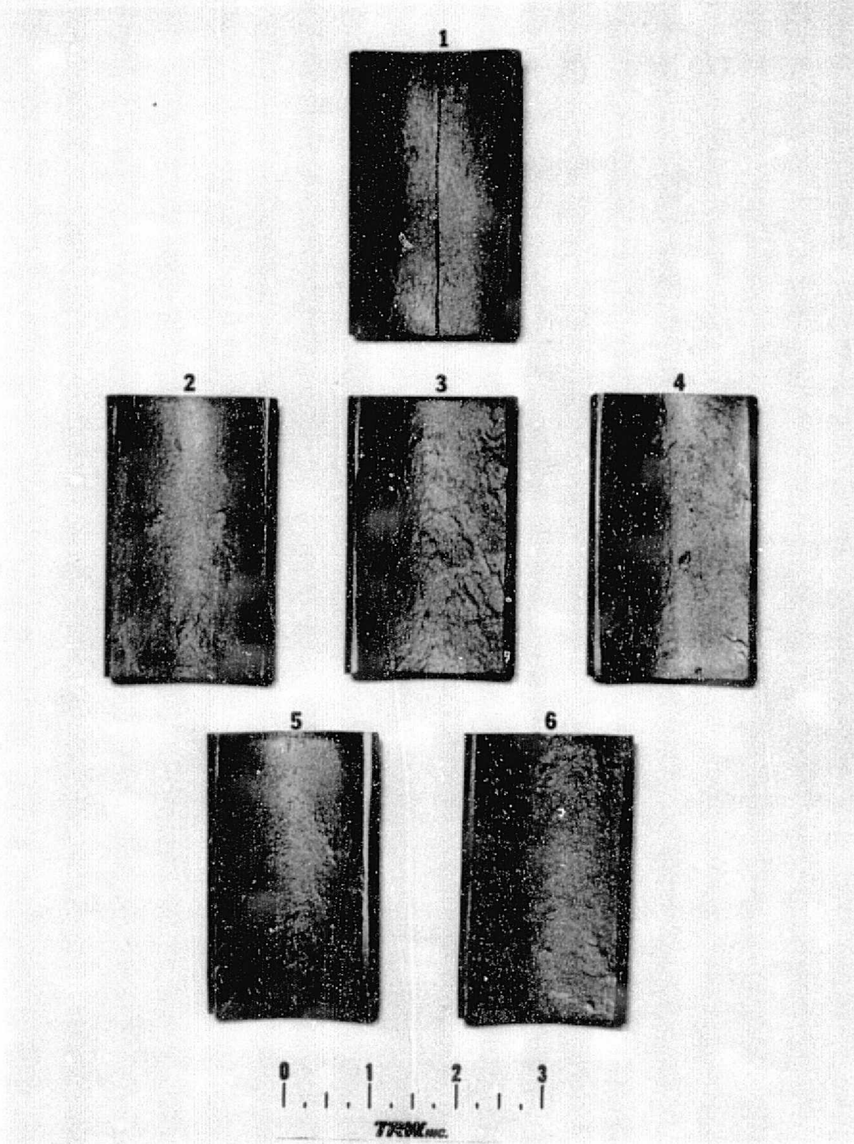
Characterization of the advanced ODS alloy forged and bent NNS with the desirable microstructure was conducted to establish the secondary processing effects on properties most essential for turbine vane application. Tensile and stress rupture tests were conducted in both the longitudinal and long-transverse directions. The sampling locations of the NNS bent plates are shown in Figure 23. Longitudinal testing was performed using a standard 6.35 mm (0.250 inch) diameter 48.26 mm (1.90 inch) long specimen with a 4.06 mm (0.160 inch) diameter x 16.51 mm (0.650 inch) long gauge section. To facilitate testing in the long-transverse direction ODS alloy extension blocks were attached by brazing (B93) to both sides of 12.7 mm (0.5 inch) long NNS sections to provide sufficient length for specimen preparation. The low NNS thickness, bend radius, and the need to locate the relatively weak braze joints in the larger cross-sectional area shoulder regions made necessary the design of a specimen with a short gauge section as shown in Figure 24.



CONCAVE SIDE

CONVEX SIDE

Figure 21 ODS Alloy Bent Plates - Cladding Not Removed



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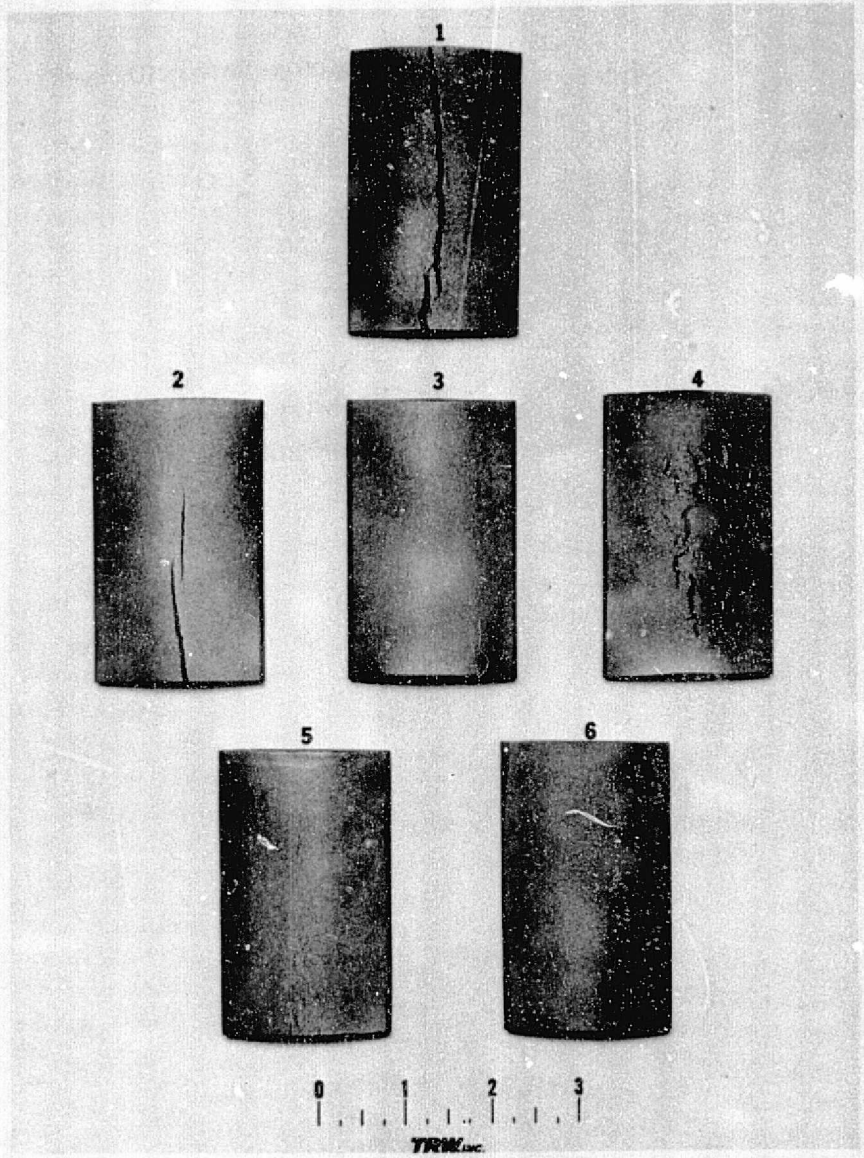

CONVEX SIDE

(b) CLADDING REMOVED

Figure 21 (Continued)

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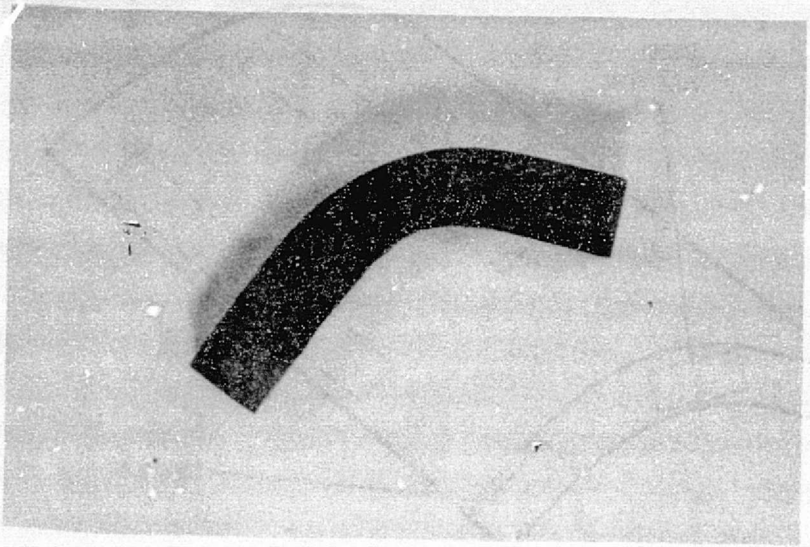


1.5X

Figure 22 MA757 Plate Bent to 12.7 MM (0.5") Radius

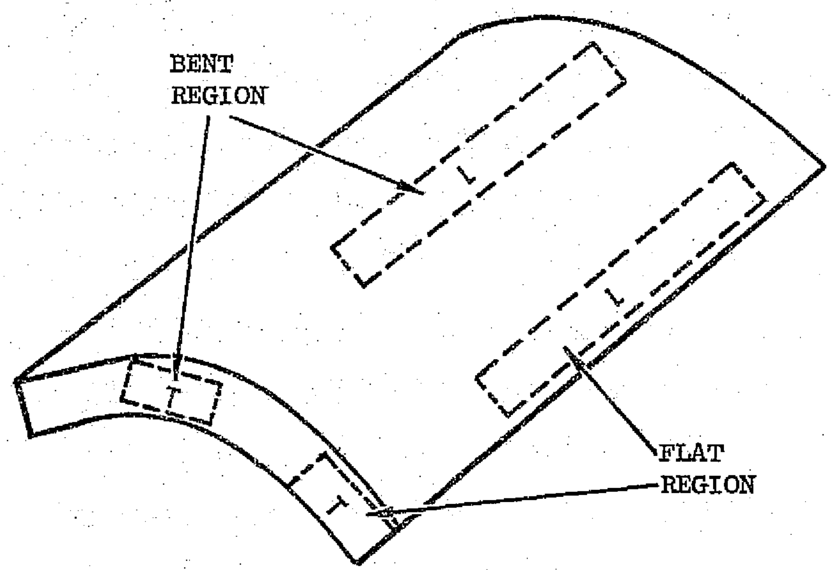


Figure 23 Samples Locations of the LPT Vane NNS

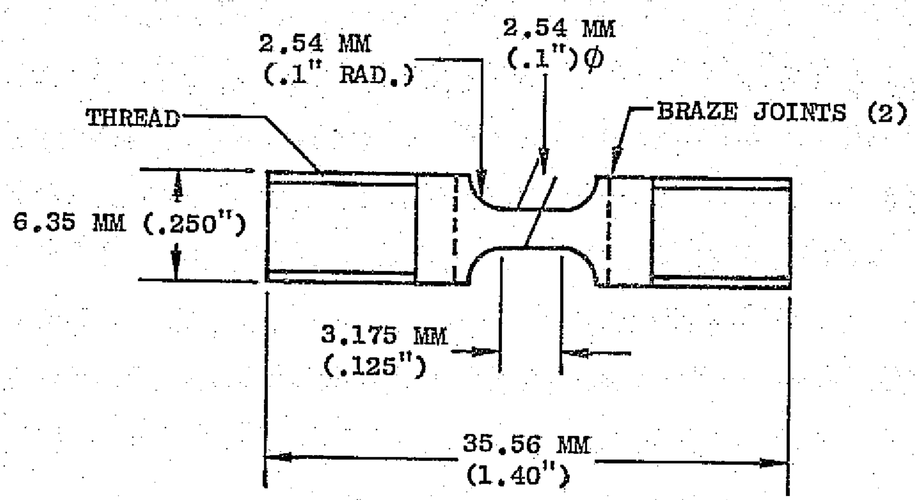


Figure 24 Assembly and Preparation of Modified Transverse Test Specimens

Tensile Evaluation - Longitudinal

Longitudinal tensile properties of the ODS alloy forged and bent kidney shapes are shown in Table VI. The MA 757 NNS, F8 Rx-2 and F8 Rx HT-2, forged in the recrystallized condition showed improved strength and ductility. Compared to the vendor furnished baseline data the ultimate tensile strength was increased on the average about 10 percent, elongation 90 percent and reduction of area by 30 percent. MA 757, F4B-3, forged in the as-rolled condition and recrystallized produce strengths comparable to the baseline accompanied with improved ductility. YDNiCrAl NNS properties were investigated only in the recrystallized and forged condition. Suitable mircostructures were not maintained at the process temperatures investigated for the forged and then recrystallized conditions. The YDNiCrAl, F10Rx-2, also achieved improved tensile properties in forge processing, espcially in ductility. Elongation increased by 30 percent and reduction of area by 170 percent. Ultimate strength was increased by 18 percent.

HDA 8077 rolled and bent plate NNS B3-2 and B6-2 were tensile tested and the results were compared to HDA 8077 typical 30.5 mm (1.2 inch) thick rectangular shaped bar. All properties were similar - within the typical variance.

TABLE VI. LONGITUDINAL TENSILE PROPERTIES OF ODS ALLOYS FORGED AT 1093°C (2000°F)

Sample No.	Material	Process Condition[1]	0.2 YS, MPa (ksi)	Ult, MPa (ksi)	El, %	RA, %
-	MA 757	Baseline	~103.4 (~ 15.0)	~117.2 (17.0)	~ 9.0	-
F4B-3	MA 757	Forge + Rx	102.7 (14.9)	109.6 (15.9)	15.3	41.2
F8Rx-2	MA 757	Rx + Forge	122.7 (17.8)	136.5 (19.8)	18.0	51.5
F8RxHT-2	MA 757	Rx + Forge + 1315°C (2400°F)	106.2 (15.4)	124.1 (18.0)	16.6	56.7
-	YD NiCrAl	Baseline	-	~82.7(~12.0)	~20.0	~28.0
F10Rx-2	YD NiCrAl	Rx + Forge	90.3 (13.1)	97.2 (14.1)	26.4	76.4
F10RxHT-2	YD NiCrAl	Rx + Forge + 1315°C (2400°F)	91.7 (13.3)	98.6 (14.3)	24.6	94.5
-	HDA 8077	Baseline	-	~110.3 (16.0)	~13.0	~10.0
B3-2	HDA 8077	Bend + Rx	92.2 (14.1)	107.5 (15.6)	10.9	17.1
B6-2	HDA 8077	Bend 1093°C (2000°F) + Rx	93.1 (13.5)	104.1 (15.1)	11.7	18.5

(1) Process conditions:

Temperature 1093°C (1900°F)
Forge reduction about 45%
Bend radius 41.91 mm (1.65")
Recrystallization (Rx)
Heat treatment (H.T.) 1315°C (2400°F)

Stress Rupture Evaluation - Longitudinal

MA 757 and YDNiCrAl forged and bent NNS were tested in stress rupture and compared to vendor furnished baseline data as shown in Table VII. Tests were conducted at 2000°F in air and 10 ksi direct load. Ductilities could not be measured because of the nature of the test specimen fractures although they are estimated to range from nil to 2.0 percent elongation. The vendor furnished baseline data is typical of rupture strengths achieved in 30.5 mm (1.2 inch) x 81.3 mm (3.2 inch) flat rolled and rectangular shaped bar. The variance is reported to be about 3.4 MPa (0.5 ksi) for constant lives.

Eight MA 757 forged NNS were tested longitudinally in stress rupture. Four test specimens (F2-1, F4B-1, F4B-2 and F4B-4) were prepared from NNS that were forged from preforms in the as-rolled condition and then recrystallized. Two test specimens (F8Rx-1 and F8Rx-3) were prepared from NNS that were forged from preforms in recrystallized condition. Two other specimens (F8RxHT-1 and F8RxHT-3) were prepared and tested from MA 757 recrystallized preforms forged to NNS and then exposed to a 2400°F one hour heat treatment. The latter two tests were designed to establish the microstructural stability of the ODS alloy forged from the recrystallized condition. Loss of the desired grain size, shape and texture through secondary recrystallization, (caused by working at too low a temperature and then a high temperature exposure) would result in degradation of properties. The ODS alloys are designed to be microstructurally stable up to at least 1371°C (2500°F). All the conditions tested indicated the stress-rupture strengths of MA 757 alloy were maintained and in most cases rupture lives were increased. Ductility improvements obtained through forging MA 757 in the recrystallized condition as determined in the tensile tests results was not evident in stress rupture indicating its dependence on strain rate.

YDNiCrAl was stress rupture tested only in the recrystallized and forged condition for reasons previously explained. Specimen 10Rx-1 was inadvertently loaded at 68.9 Pma (10 ksi) and lasted one hour at 1093°C (2000°F). Compared to as-received recrystallized (YDNiCrAl General Electric test data, the typical stress for a one hour life at 1093°C (2000°F) would be 55.1 MPa (8.0 ksi), thus indicating that a significant strength increase was probably achieved in the forged YDNiCrAl, the strength level was, however, still below that of the MA 757 and HDA 8077 alloys.

Rolled and bent plate HDA 8077 NNS were evaluated in stress rupture. Specimens were prepared from the radius produced by transverse bending and tested (longitudinal microstructure) at 1093°C (2000°F) and 68.9 MPa (10 ksi) load. The tests results indicated HDA 8077 bent plate strengths were comparable to the MA 757 forged NNS.

Stress Rupture Evaluation - Long Transverse

MA 757 simulated NNS forging F4B forged to a 50% reduction in thickness at 1900°F in the recrystallized condition was stress rupture tested in long-transverse microstructure at 1038°C (2000°F) and 34.5 MPa (5 ksi) direct load. The rupture life was comparable to vendor furnished baseline data and is shown in Table VIII. Typical baseline data for extruded, rolled, 30.5 mm (1.2 inch) thick x 76.2 mm (3.0 inch) width, and recrystallized MA 757 in the long-trans-

TABLE VII. LONGITUDINAL STRESS RUPTURE PROPERTIES OF ODS ALLOYS FORGED AT 1093°C, 68.9 MPa (2000°F, 10 ksi)

Sample No.	Material	Process Condition (1)	Life, Hrs
-	MA 757	Rx	~ 30 (2)
F2-1	MA 757	Forged (25%) + Rx	28
F4B-1	MA 757	Forged + Rx	119
F4B-2	MA 757	Forged + Rx	27
F4B-4	MA 757	Forged + Rx	46
F8Rx-1	MA 757	Rx + Forged	86
F8Rx-3	MA 757	Rx + Forged	109
F8RxHT-1	MA 757	Rx + Forged + H.T.	85
F8RxHT-3	MA 757	Rx + Forged + H.T.	111
-	YD	Rx	2 (at 8.0 ksi)
F10Rx-1	YD	Rx + Forged	1
B3-1	HDA 8077	Bent plate	60
B3-3	HDA 8077	Bent plate	57
B6-1	HDA 8077	Bent plate 93°C(200°F)	55
B6-3	HDA 8077	Bent plate	82

TABLE VIII. LONG TRANSVERSE STRESS RUPTURE PROPERTIES OF ODS ALLOYS FORGED AT 1093°C, 34.5 MPa (2000°F, 5 ksi)

-	MA 757	Rx	~ 10 (2)
F4B	MA 757	Forged + Rx	7

---

(1) Process conditions unless noted otherwise:

Temperature 1038°C (1900°F)
Forge reduction about 45%
Bend radius 41.9 mm (1.65 inches)
Recrystallized (Rx)
Heat Treated (H.T.) 1315°C (2400°F)

(2) Vendor data

verse direction at 1038°C (2000°F) and 34.5 MPa (5 ksi) is about 10 hours rupture life. A specimen prepared from extruded, rolled, forged and recrystallized F4B lasted 7 hours indicating that the desirable properties and integrity were maintained.

Crystallographic Orientation Analysis

Dynamic modulus of elasticity determinations of the MA 757 bent plate simulated NNS were conducted to establish the effects of transverse strain in subsequent recrystallization heat treatment. ODS alloys are highly processed in a single direction to achieve the (001) low modulus longitudinal texture and have a low tolerance for lateral and tangential material flow. Relatively small strains in a direction other than longitudinal will promote non-desirable crystallographic textures and higher modulus material than tolerable for turbine vane application. A 6.35 mm (0.250 inch) diameter x 76.2 mm (3.0 inch) long test specimen was prepared from the flat (unstrained) region and one from the bent (laterally strained) region of the bent plate and dynamically tested from R.T to 982°C (1800°F) as illustrated in Figure 25. Dynamic modulus values are determined by the following calculation:

Dynamic modulus of elasticity calculation:

$$E = .0041627 \frac{WL^3}{D^4} f^2$$

where E = Modulus, Pascals (psi)

W = Spec. Weight, Kilograms (lbs)

L = Spec. Length, Meters (inches)

D = Spec. Diameter, Meters (inches)

f = First Flexure Resonance (H_z)

The modulus of elasticity values of strained and unstrained NNS regions as a function of temperature are shown in Figure 26. The modulus values from both regions are well within the vane component specification of 172,350 G Pa (25,000,000 psi)or lower at R.T.

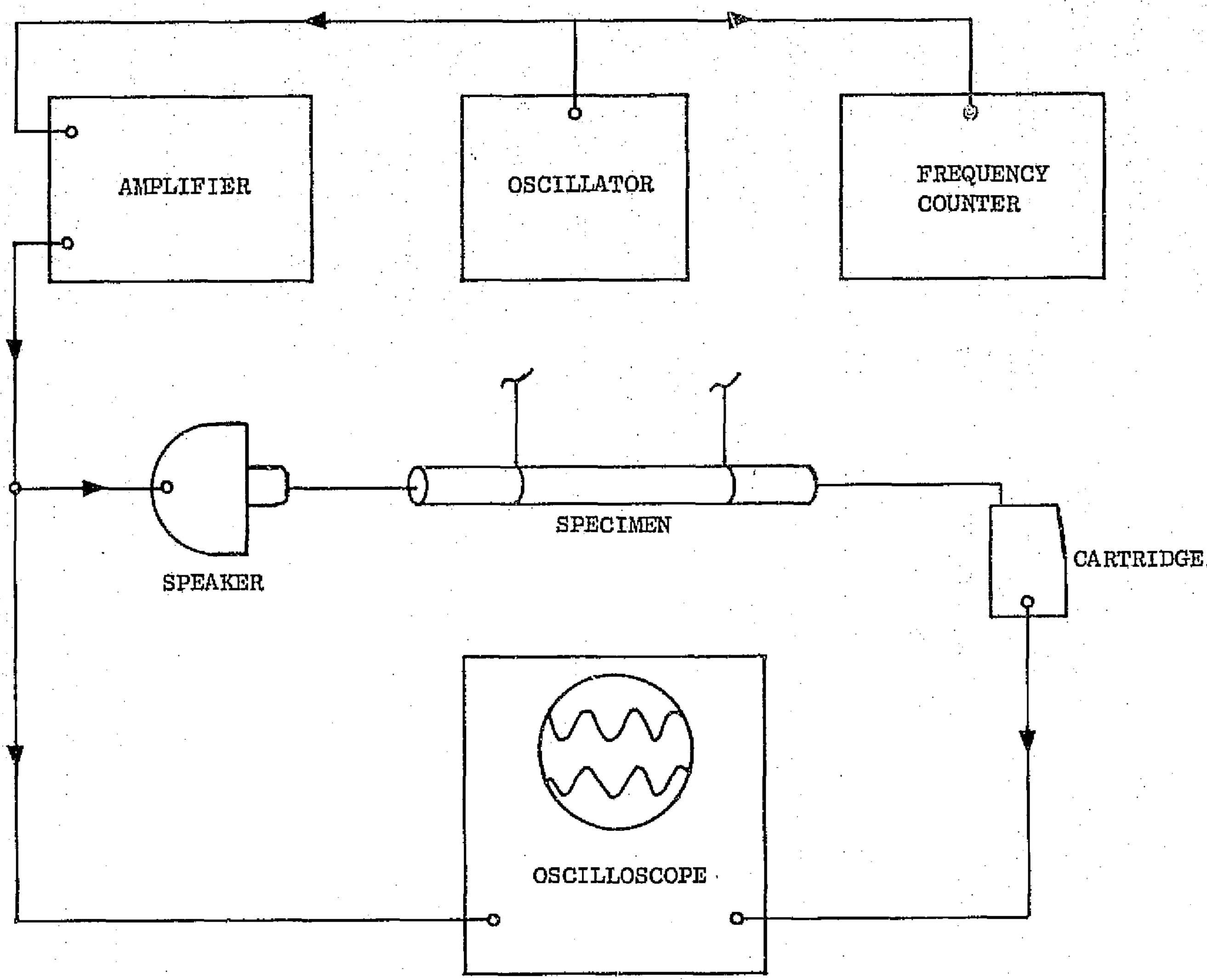


Figure 25 Dynamic Modulus Determination Technique

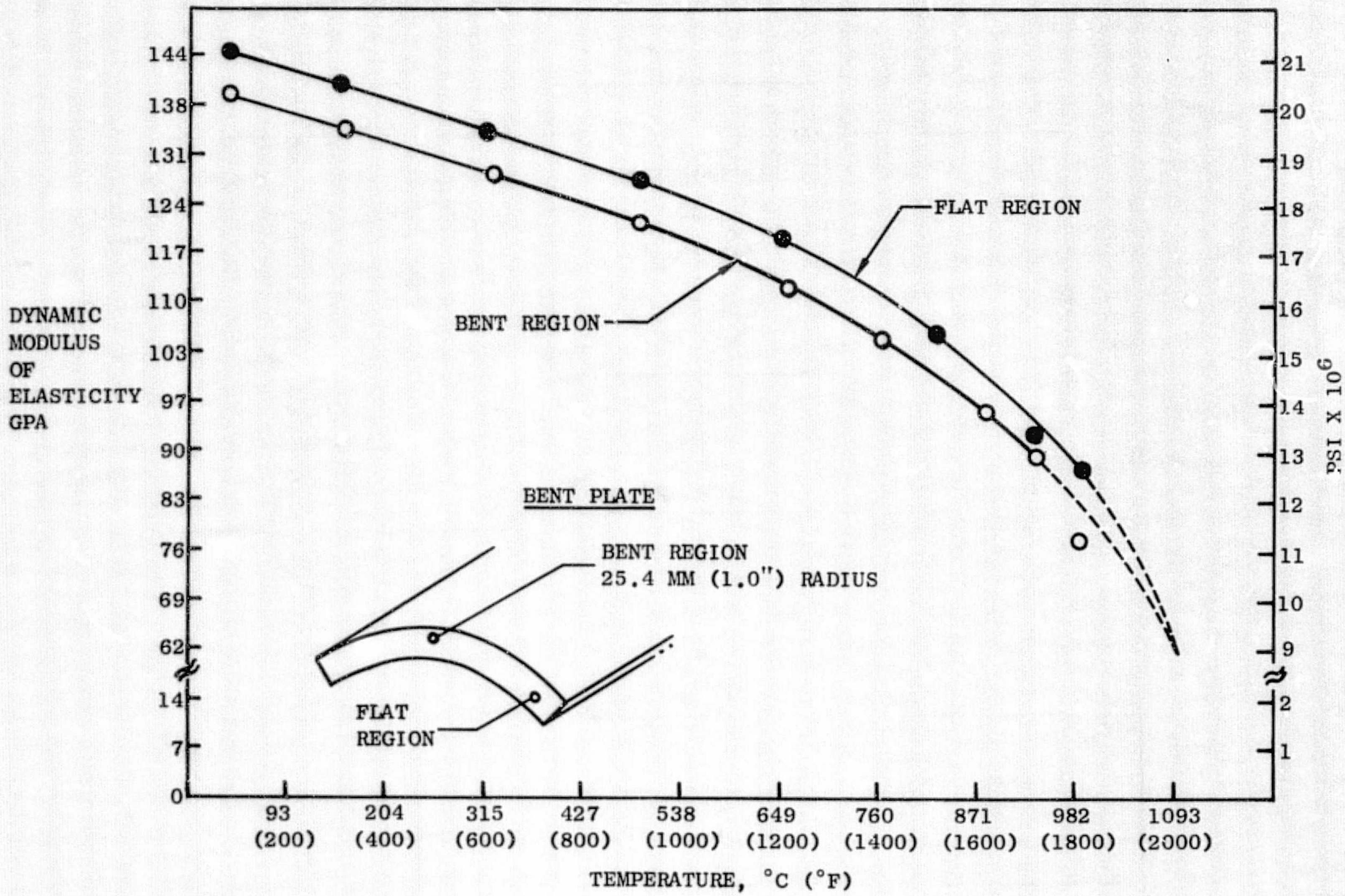


Figure 26 MA757 LPT Vane NNS Longitudinal Dynamic Modulus

2.5 Task II - F101 LPT Vane Near-Net Shape Process Establishment

The purpose of Task II of the program was to establish an F101 low pressure turbine vane near-net shape process from the secondary conversion techniques investigated in Task I. Plate bending was selected because it was determined to be the most cost effective as well as being simpler and more amenable to all ODS alloys and vendors. The plate bending approach is estimated to save about 40% of the manufacturing cost for producing the NNS vane through improved material utilization and reduced machining costs. The shape produced was a uniform cross-section plate bent to the curvature and twist of the vane including a minimum .635 mm (0.025") envelope.

2.5.1 ODS Alloys & Preparation

The advanced ODS alloys, MA 757 and YDNiCrAl were selected for the Task II LPT vane near-net shape process establishment. MA 757 in a commercially available size, 30.5 mm (1.2") thick x 73.7 mm (2.9") wide rectangular bar, was used. Vendor property data showed stress rupture strength adequate for the F101 LPT vane application. The YDNiCrAl, however, designed for improved ductility and thermal fatigue resistance, was believed to be deficient in longitudinal strength. To improve the YDNiCrAl strength, the Y_2O_3 dispersoid content was increased (doubled) to 2.0%. Some sacrifice in ductility was expected, however.

The vendors were requested to prepare nominally 7.37 mm (.291") thick x 66.55 mm (2.62") wide plates in the as-rolled (unrecrystallized) condition. Huntington Alloys experienced difficulties producing MA 757 of the 7.37 mm (0.29") thickness with suitable microstructure. Huntington's rolling mill and furnace facilities were designed for thicker products and were not easily adaptable to rolling plate. Their conveyor roller spacing prevents the rolling of starting lengths shorter than about 1.5 meters (5 ft.) which results in long lengths at plate thickness. Huntington's inability to reheat and transfer the long thin MA 757 strip to the mill fast enough would cause excessive loss of temperature during rolling. Because of this situation Huntington supplied General Electric with 30.5 mm (1.2") thick x 73.7 mm (2.9") wide as-rolled and steel clad MA 757 for General Electric plate rolling. Rolling parameters were established using a 20.3 cm (8") diameter x 25.4 cm (10") long, two-high roll mill and nearby electric furnace.

The General Electric plate rolling, was successful. Segments of the 30.5mm (1.2") thick bar were rolled at 1010°C (1850°F), 1065C (1950°F), 1150°C (2100°F) and 1205°C (220°F) using a 10% reduction per pass to the 7.37mm (0.29") thickness. The ODS alloy was rolled with the mild steel extrusion jacket intact and was reheated between each pass. After rolling, the plate was exposed to a recrystallization anneal heat treatment and microstructurally evaluated. Material processed at 1010°C (1850°F) exhibited a good grain size, shape and (001) crystallographic orientation. The materials processed at 1065°C (1950°F) and higher contained increasing amounts of an undesirable microstructure. The rolled 7.37mm (9.29") thick material was evaluated for bend formability. Sections of all four plates in the as-rolled and pickled condition were wrapped in fiber frax insulation, heated to 1150°C (2100°F) in air and bent to about a 13mm (1/2") radius to simulate the F101 LPT vane near-net shape. Plates rolled at 1010°C (1850°F) and 1065°C (1950°F) bent well; no cracks were detected. Plates prepared at 1150°C (2100°F)

and 1206°C (2200°F) had dynamically recrystallized during rolling and caused severe cracking when subjected to bending. The successfully bent plates were recrystallization annealed, microstructurally evaluated and the bend areas compared to the as-rolled and crystallized plates. No obvious differences were detected. Bending had not been detrimental to achievement of the desired microstructure.

To demonstrate reproducibility and optimize plate processing temperatures 39.5mm (1.2") thick bar sections were rolled at 980°C (1800°F) and 1010°C (1850°F). A cursory evaluation of these later prepared plates in the as-rolled and recrystallized conditions indicated the plate rolling process was reproducible and produced good microstructures.

General Electric prepared a sufficient quantity of MA757, 7.37mm (0.29") thick plate preform material for the completion of the program. Huntington Alloys planned to continue to develop a plate rolling process although commercial ODS alloy plate was not to be available until after the program's completion.

Four 30.5mm (1.2") thick, x 73.7 (2.9") wide rectangular shaped bars were rolled at 1025°C (1875°F) to 7.37mm (0.29") thick x 91.4mm (3.6") wide. The ODS alloy was heated in air and rolled with the mild steel extrusion clad intact using 10% reduction per pass. After rolling, the steel jacket was removed in a HNO_3 and H_2O solution and the ODS alloy plates were inspected for integrity and dimensional tolerance. Integrity was excellent; no cracking was detectable by zyglo examination. The plate surfaces were undulated, varying about .25mm (0.010") because of the severe oxidation of the steel jacket during rolling. The MA757 rolled plates were examined for microstructural variation. Samples from each end and the middle of all four plates were exposed to a recrystallization anneal heat treatment of 1205°C (2200°F-1315°C (2400°F), 38°C (100°F) increase per hour. All the recrystallization annealed samples exhibited a desirable grain size, shape and crystallographic orientation in macroscopic and microscopic evaluations. The plates were also sampled and exposed at the 1150°C (2100°F) bend process temperature and examined for undesirable recrystallization. None was detected. Recrystallization is detrimental to bending in which transverse tensile strains are encountered.

Special Metals, utilizing a laboratory size rolling facility prepared and supplied the plate configuration, but also experienced problems with achieving the desired microstructure. Samplings from the plate material heat treated to 1345°C (2450°F) exhibited a "cored" microstructure somewhat like that produced in the extruded Task I gullwings and described in an earlier section of the report. The central region of the YDNiCrAl plate's transverse cross-section contained highly reflective grains in the macroetched condition typical of high modulus orientations. Although the microstructure of the YDNiCrAl was not satisfactory for vane application, the material was retained in the Task II near-net shape process establishment effort for experience in handling that alloy. There was an envelope of about 2.5mm (0.1") thick of desirable microstructure in the YDNiCrAl plate. Because these outer areas are the ones worked in bending, the YDNiCrAl plate was believed to be suitable for characterization of the process.

2.5.2 Tooling & Equipment

The tooling was fabricated from A1S1 H-12 alloy and was designed as shown in Figure 27 to form a NNS with approximately a 1.25mm (.05") envelope from which General Electric could finish machine LPT vanes (#9942M44). The preform and the shape to be formed are shown in Figure 28. The starting material plate width is the same as the die cavity width with allowances for thermal expansion. The tooling was heated with electrical resistance cartridge heaters and maintained at about 205C (400F). The die and punch were sprayed with graphite lubricant. No reduction in cross-section was planned for the plate bending operation. The TRW hot bending facility is shown in Figure 29.

2.5.3 Near-Net Shape Processing

Thirty as-rolled (unrecrystallized) MA757 and YDNiCrAl plate segments 7.4mm (.29") thick x 55mm (2.2") wide x 80mm (3.2") long were bent to the near-net shape. The ODS alloy plate segments were heated to various temperatures of 1120°C (2050°C), 1150°C (2100°F) and 1175°C (2150°F) for 15 minutes in a box furnace and bent the curvature and twist of the F101 LPT vane. Transfer times from the furnace to the near-net shape die were nominally 3-4 seconds and the bending time was of the order of four seconds.

The process temperatures were selected by ODS alloy plate bending experiments at General Electric which indicated the desirable microstructure and texture could be maintained if the transverse bending was performed at a temperature low enough to prevent recrystallization and high enough to minimize cold work.

Preform process conditions included: 1) bare, 2) glass coated (two types) and 3) wrapped in fiber frax. The materials, process conditions and results are reported in Table IX. The MA757 and YDNiCrAl NNS segment are shown in Figure 30.

MA757 Bend Processing

Nineteen MA757 plates were processed to near-net shape. Cross-sectional plot (10X) samplings showed the target configuration was achieved and suitable for the manufacturing of F101 LPT vanes. Three cross-sectional plots, as shown in Figure 31, were made at ends and middle of each near-net shape sampled. These were superimposed on 10X mylar engineering drawings of the LPT vane contours.

Of the nineteen pieces processed, sixteen were bent at 1150°C (2100°F) and below without the glass type A coating. Fourteen bent well without cracking. Two NNS, Nos. 16 and 17 bent at 1150°C (2100°F) did experience some small surface tears. NNS No. 29 was bent bare at 1175°C (2150'F) and sufferred severe surface tears. As suspected, the MA757 as-rolled plate had recrystallized during heating to 1175°C (2150°F). This situation not surprisingly promoted severe cracking during bending.

TABLE IX. ODS ALLOY LPT VANE NNS PROCESS CONDITIONS

I.D.	Material(1)	Bend Temp. °C (°F)	Preform Surface Conditions	Characteristics: Shape	Characteristics: Integrity	Characteristics: Recrystallized Macrostructure
34	MA 757	1120 (2050)	Bare(2)	Good	Good	Good(3)
32	MA 757	1120 (2050)	Glass B	Good	Good	Good
1	MA 757	1150 (2100)	Bare	Good	Good	Dual(5)
2	MA 757	1150 (2100)	Bare	Good	Good	Good
3	MA 757	1150 (2100)	Bare	Good	Good	Dual(5)
4	MA 757	1150 (2100)	Bare	Good	Good	Good
5	MA 757	1150 (2100)	Bare	Good	Good	Good
6	MA 757	1150 (2100)	Bare	Good	Good	Retained by TRW
13	MA 757	1150 (2100)	Bare	Good	Good	Good
14	MA 757	1150 (2100)	Bare	Good	Good	Marginal(4)
15	MA 757	1150 (2100)	Bare	Good	Good	Marginal
16	MA 757	1150 (2100)	Bare	Good	Few small surface tears	Good
17	MA 757	1150 (2100)	Bare	Good	Few small surface tears	Good
25	MA 757	1150 (2100)	Bare	Good	Good	Good
28	MA 757	1150 (2100)	Bare	Good	Good	Dual(5)
18	MA 757	1150 (2100)	Fiber Frax Wrapped	Good	Good	Marginal
19	MA 757	1150 (2100)	Glass A	Good	Long. surface tears - convex side	Dual
20	MA 757	1150 (2100)	Glass A	Good	Long. surface tears - convex side	Marginal
29	MA 757	1175 (2150)	Bare	Good	Severe surface tears - convex side	Marginal

TABLE IX. ODS ALLOY LPT VANE NNS PROCESSING CONDITIONS

I.D.	Material (1)	Bend Temp. °C (°F)	Preform Surface Conditions	Characteristics: Shape	Integrity	Recrystallized Macrostructure
35	YD	1120 (2050)	Bare	Good	Good	Dual
33	YD	1120 (2050)	Glass A	Good	Good	Dual
9	YD	1150 (2100)	Bare	Good	Good	Dual
10	YD	1150 (2100)	Bare	Good	Good	Dual
11	YD	1150 (2100)	Bare	Good	Good	Dual
12	YD	1150 (2100)	Bare	Good	Good	Dual
27	YD	1150 (2100)	Bare	Good	Good	Dual
21	YD	1150 (2100)	Glass B	Good	Long. surface tears - convex side	Dual
22	YD	1150 (2100)	Glass B	Good	Long. surface tears - convex side	Dual
30	YD	1175 (2150)	Bare	Good	Good	Dual
31	YD	1175 (2150)	Bare	Good	Good	Dual

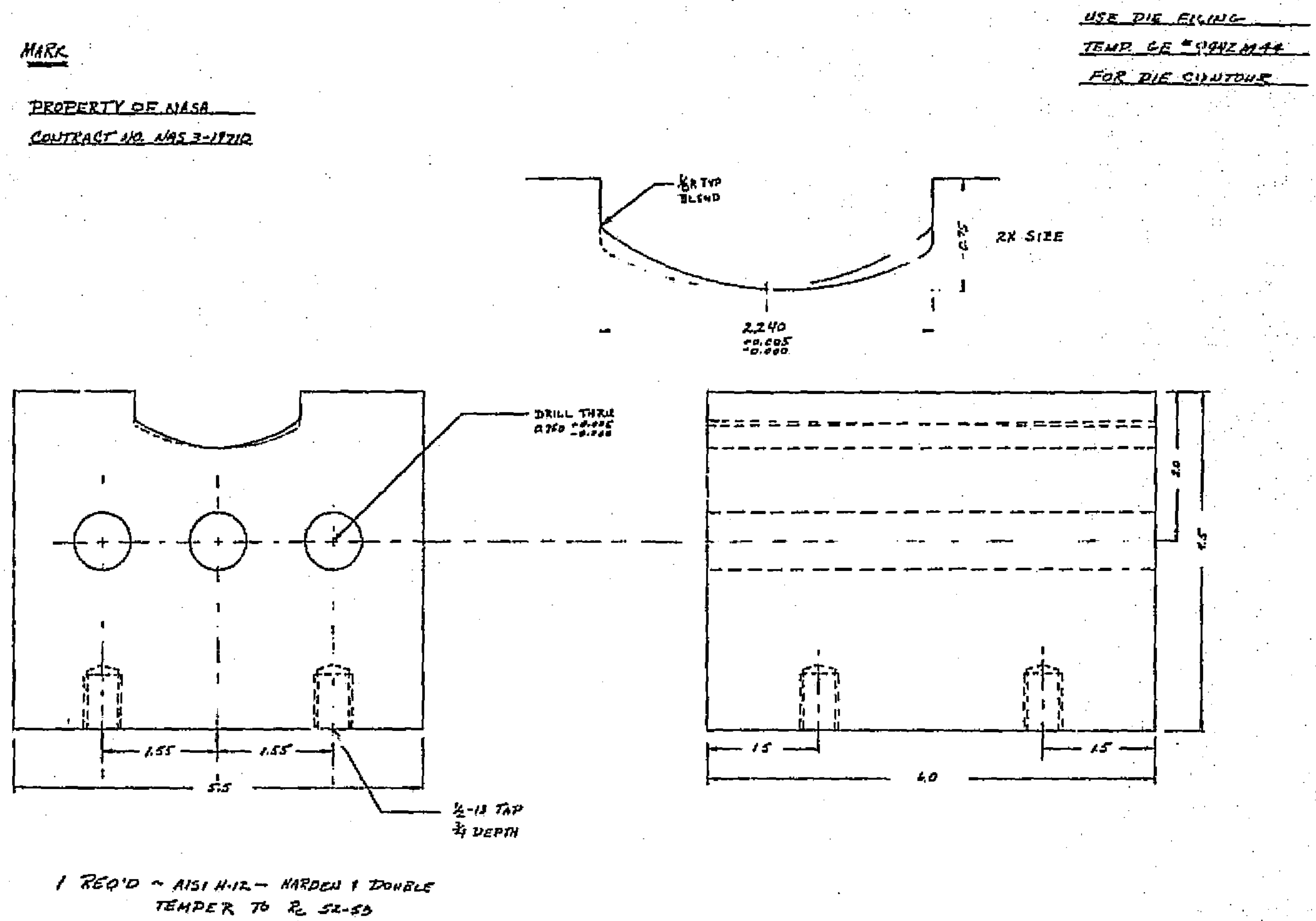
(1) As-rolled condition (unrecrystallized).

(2) Unclad

(3) Desirable [001] texture, grain size and shape

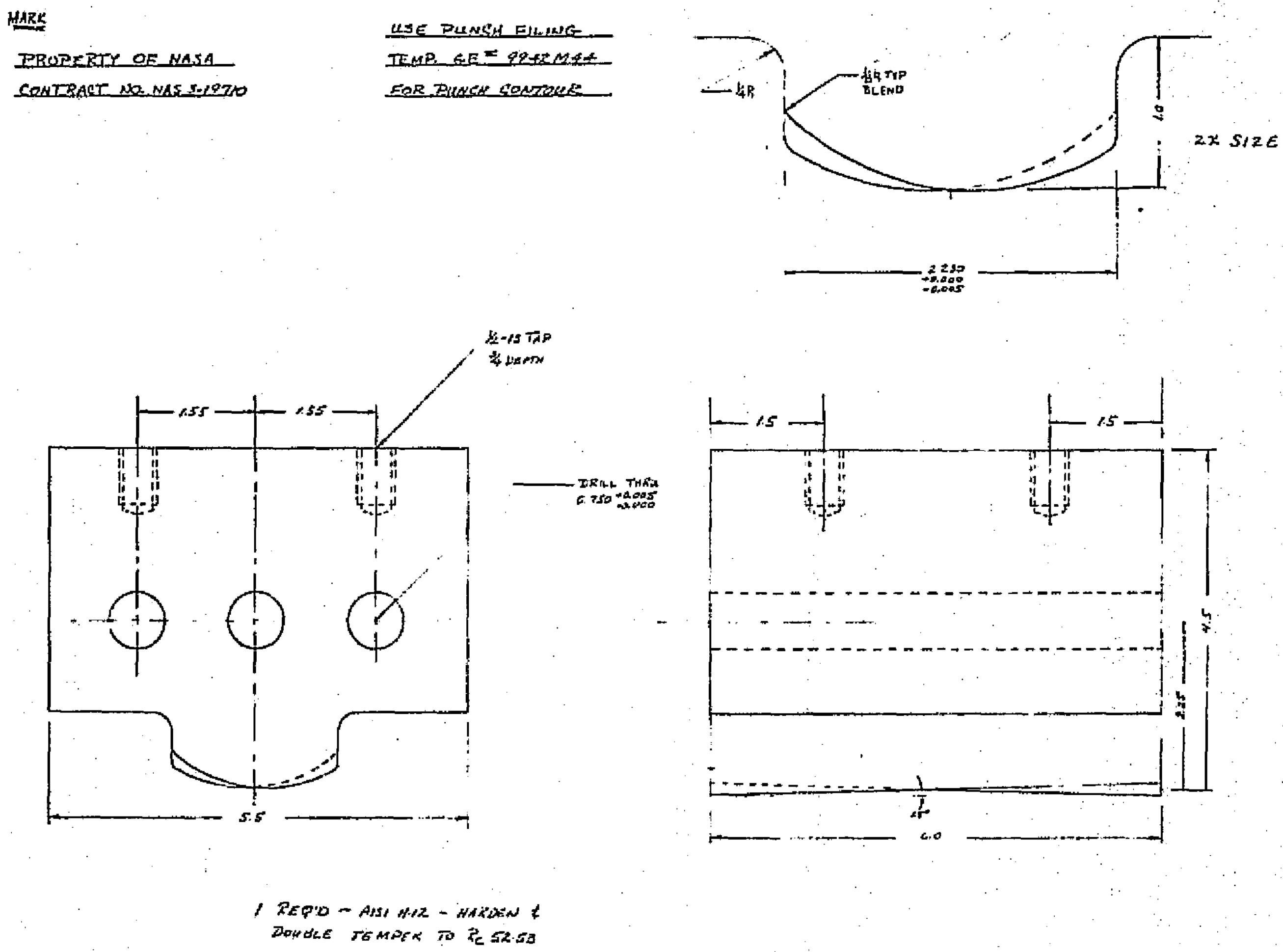
(4) Probably meets the 17.2 x 10^4 MPa (25, x 10^6 psi) modulus requirement but is not recommended for service.

(5)



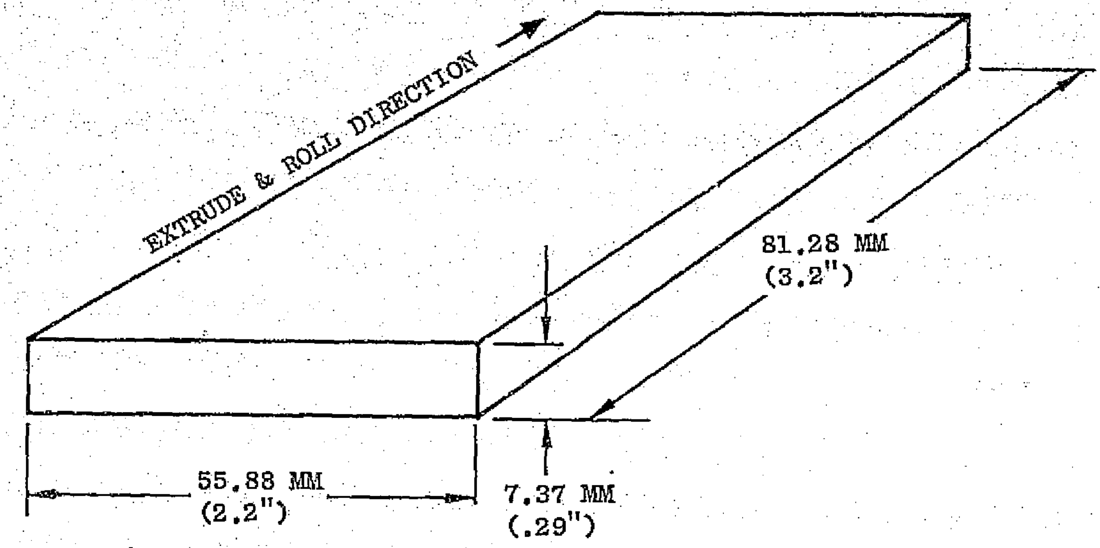
(a) DIE BODY

Figure 27 ODS Plate Bending Tooling Design

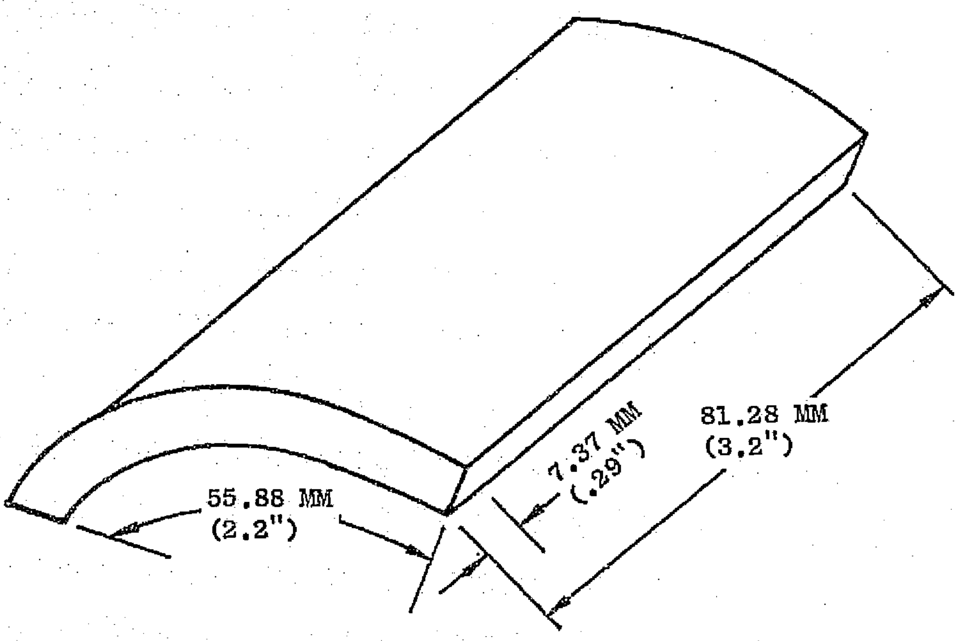


(b) DIE PUNCH

Figure 27 (continued)

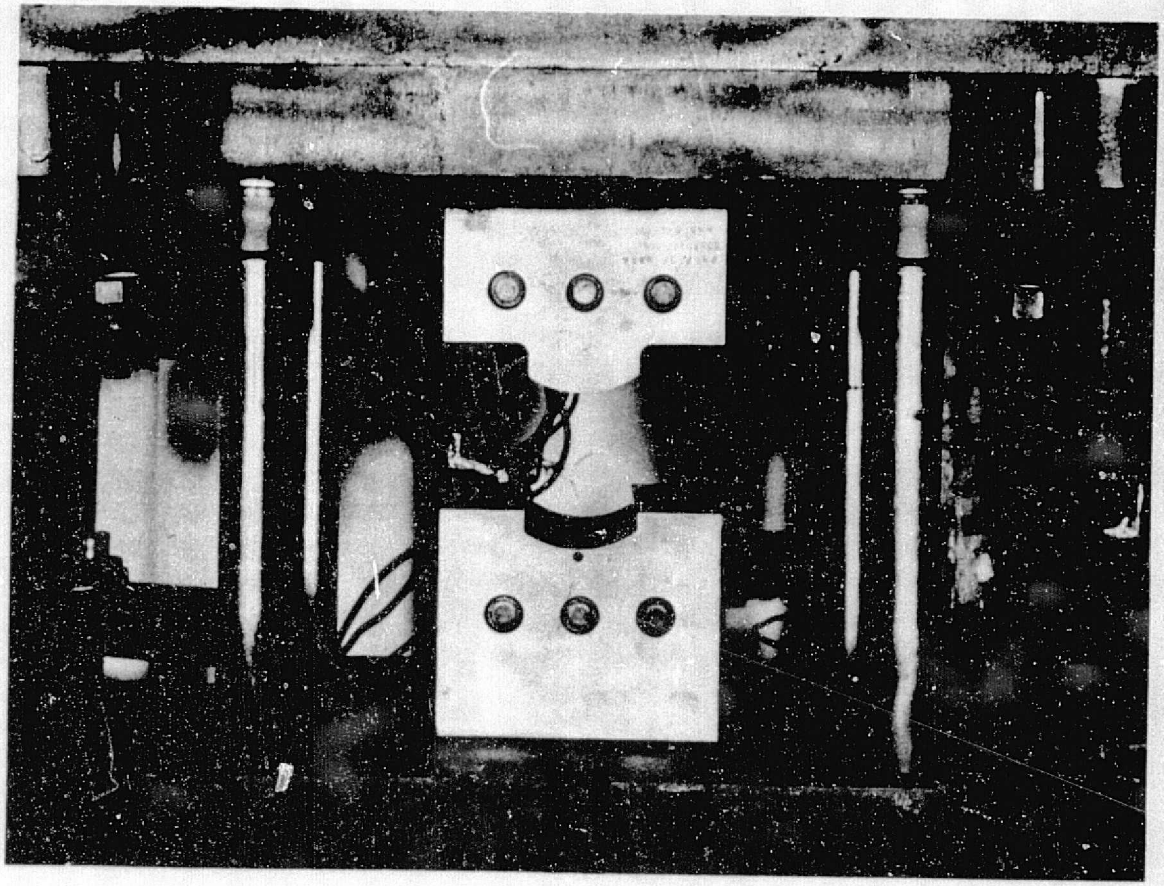


(a) PREFORM



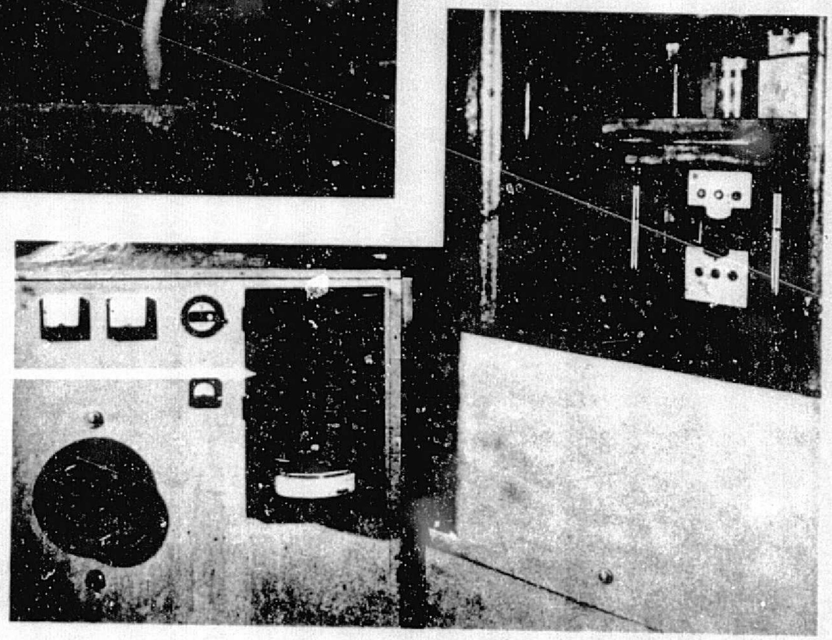
(b) NNS

Figure 28 F101 Low Pressure Turbine Vane Preform and NNS



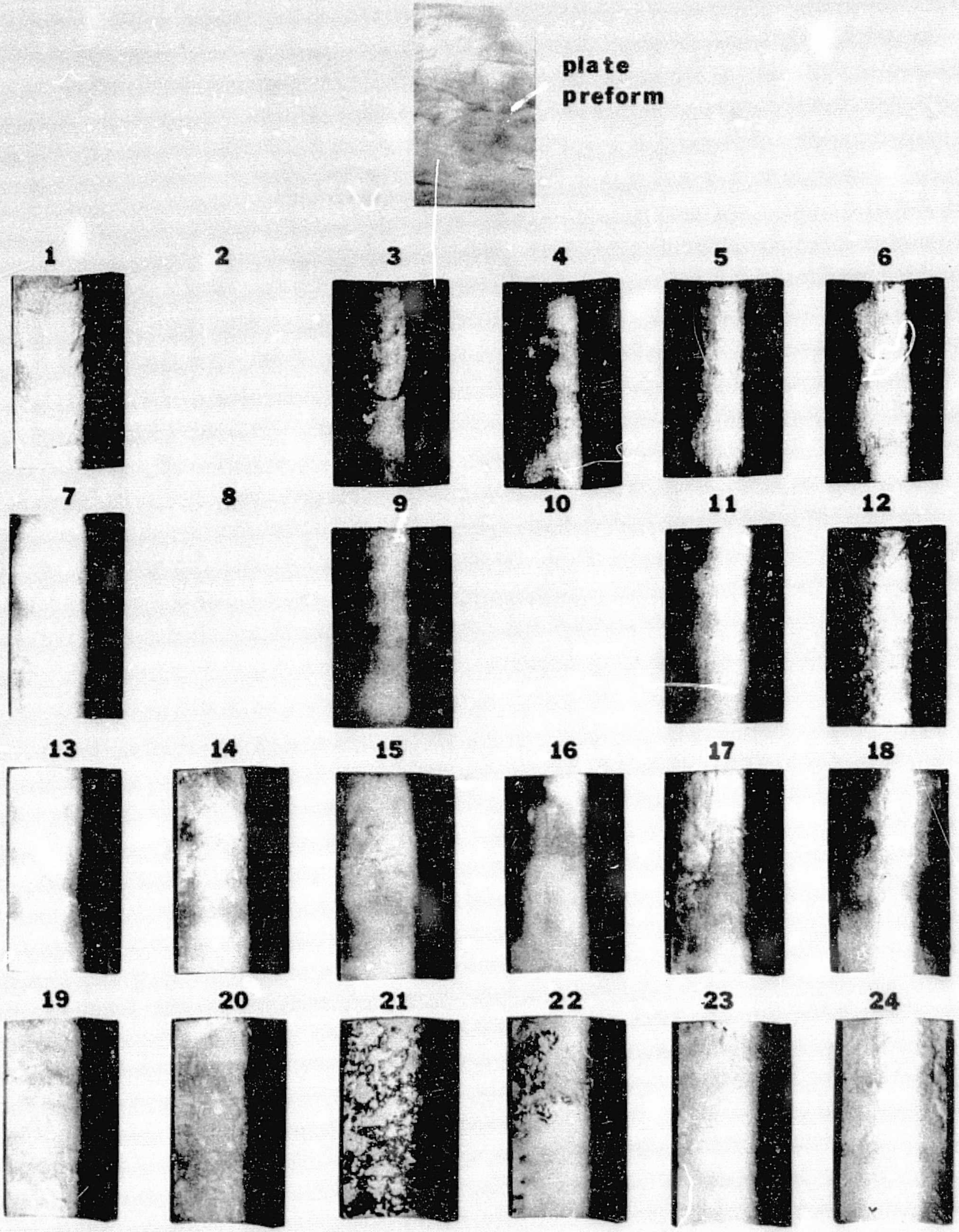
b. Closeup of Bending Tooling

Temperature
Controller



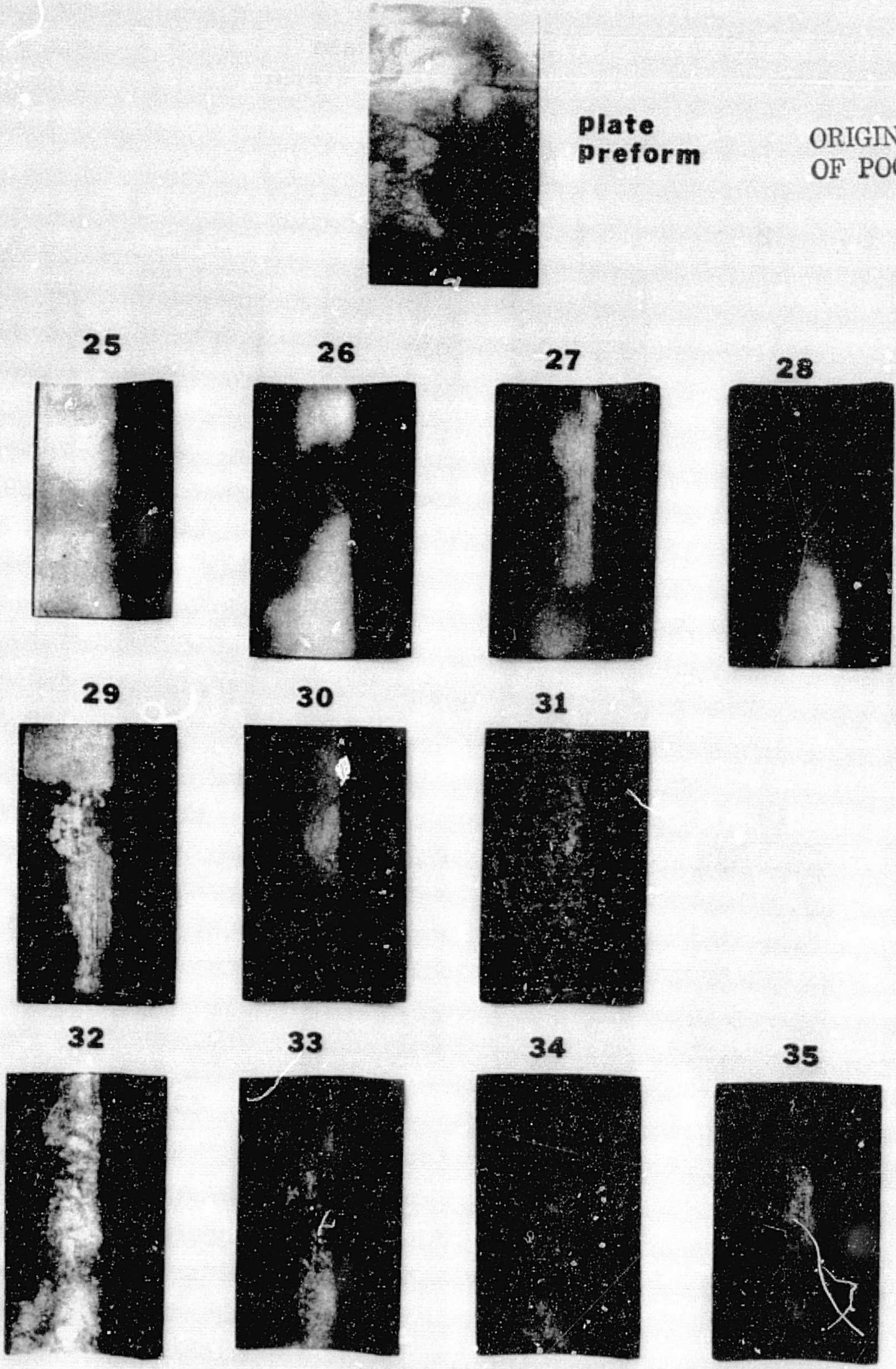
a. Overall View of Facility

Figure 29 TRW Hot Plate Bending Facility



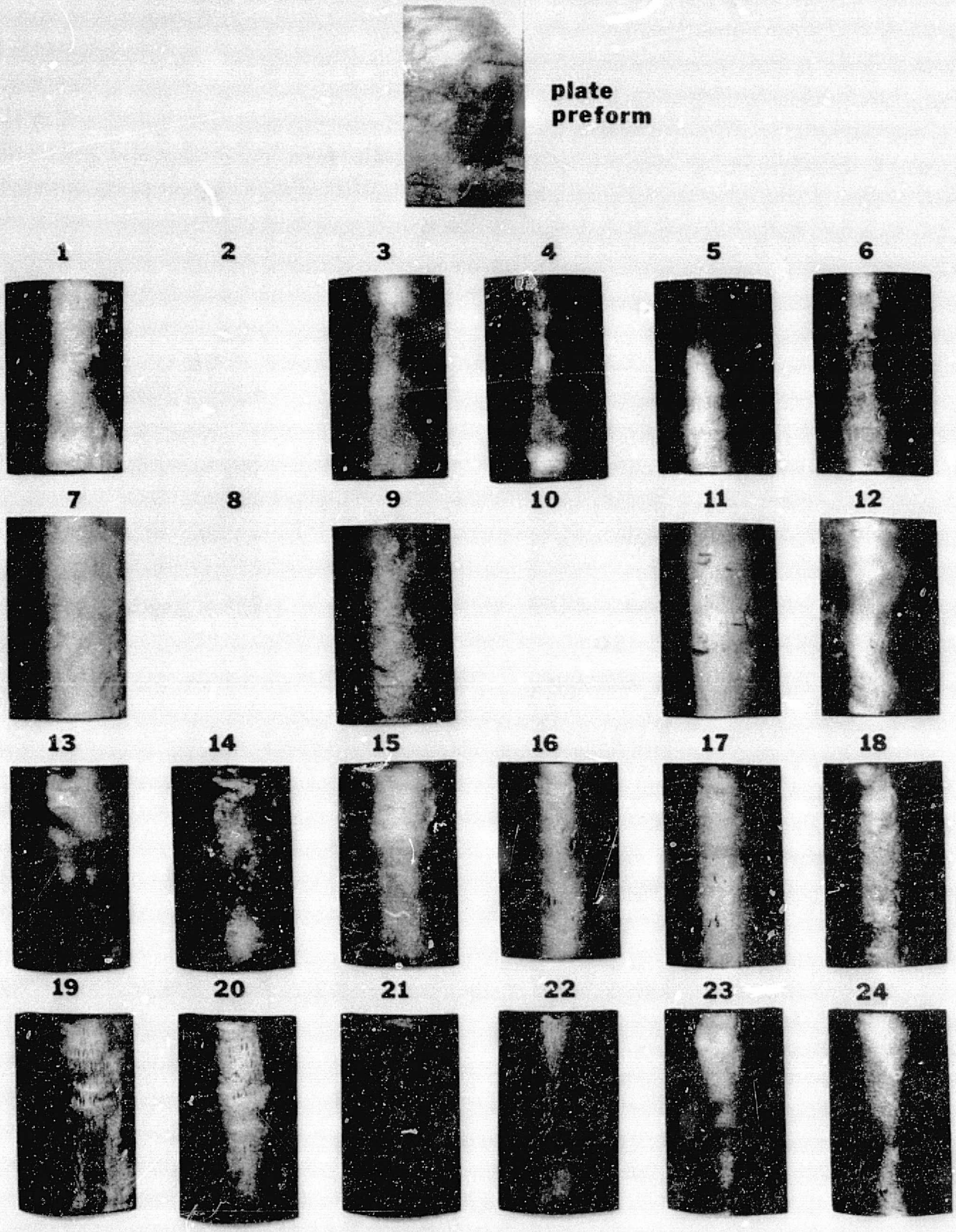
(a) CONCAVE SIDE

Figure 30 MA757 And YDNiCrAl Bent Plate NNS



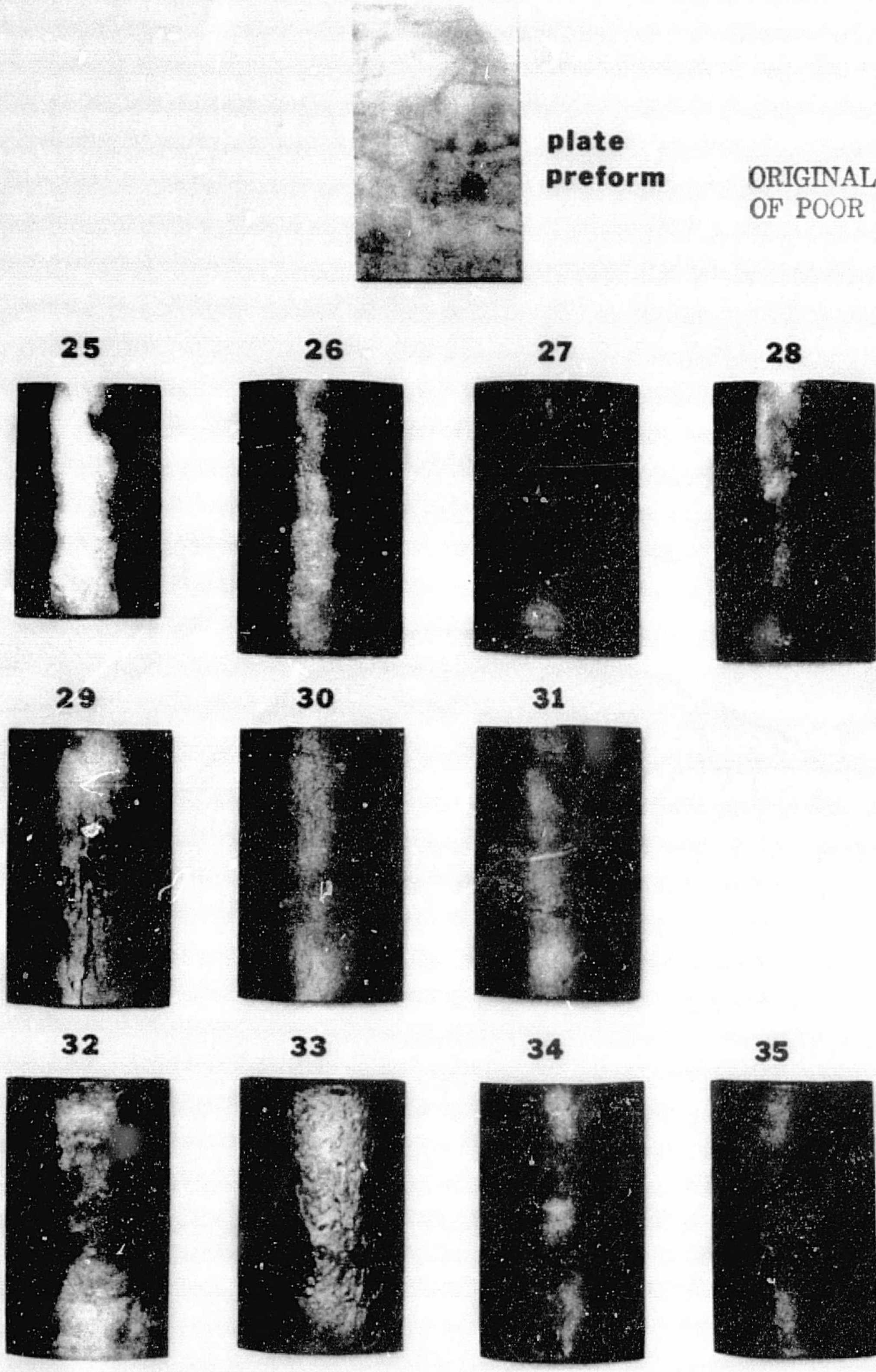
(c) CONCAVE SIDE

Figure 30 (Continued)



(b) CONVEX SIDE

Figure 30 (Continued)



(d) CONVEX SIDE

Figure 30 (Continued)

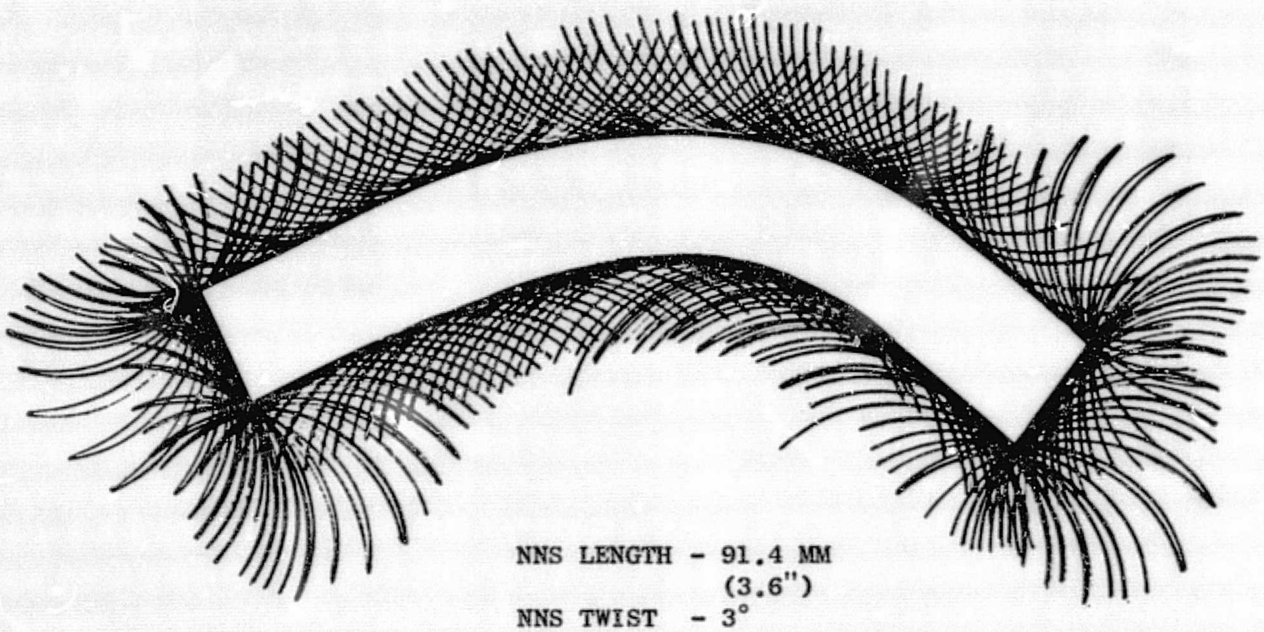


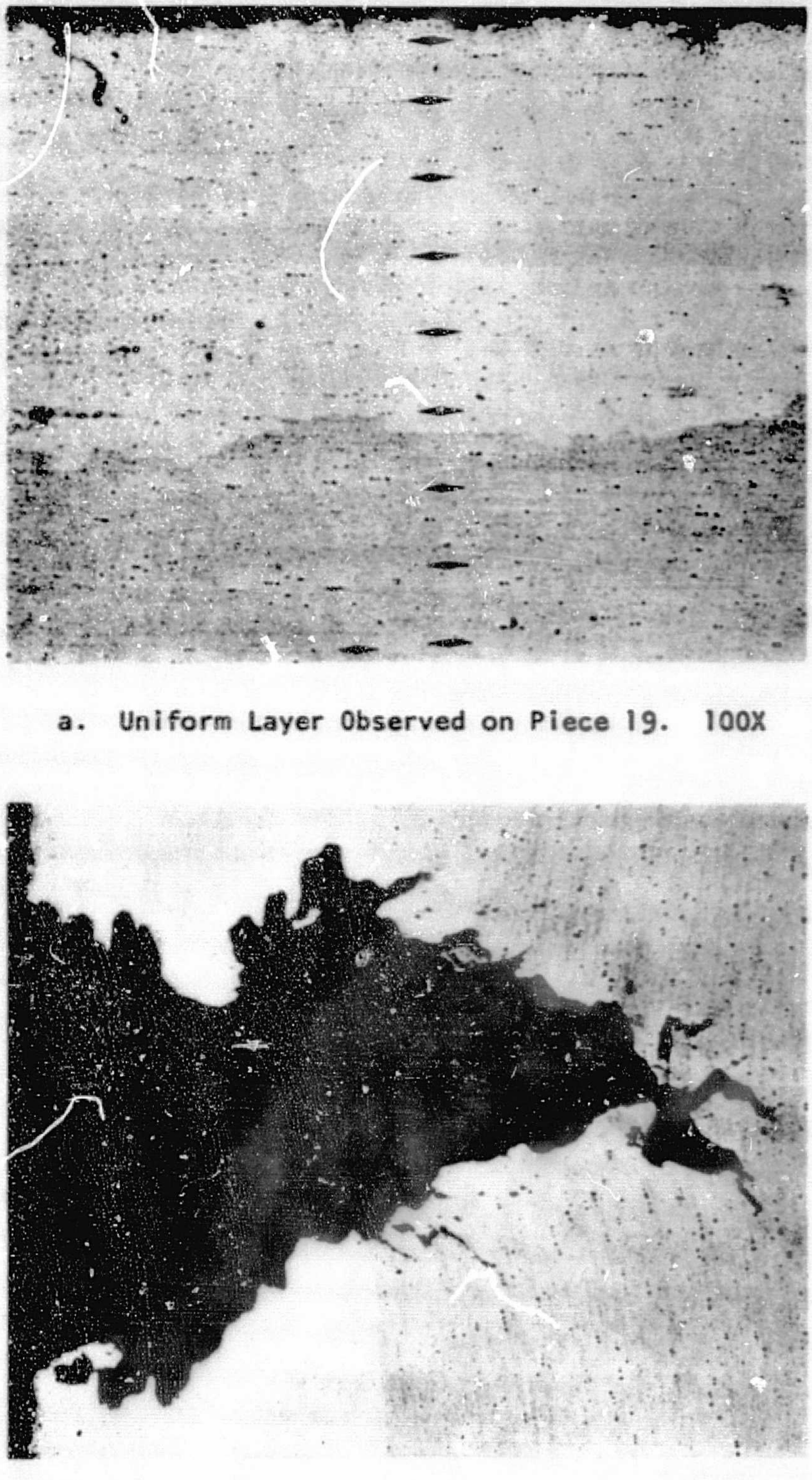
Figure 31 Cross-Sectional Plot (10X) Sampling of LPT Vane NNS Configuration - Reduced to 2.3X

Three surface preparations were used to reduce the heat loss from the part to the warm tooling - glass coatings (type A and B) and fiber frax insulation. The type A glass coating was a sodium aluminum borosilicate. The glass coatings effectively reduced heat loss although the glass A type at the 1150°C (2100°F) bend temperature, NNS Nos. 19 and 20, caused surface tears during bending.

TRW determined that surface recrystallization was the cause after microprobe and spectrographic analysis on No. 19 showed appreciable surface chemistry changes. Metallographic and hardness examinations of No. 19 revealed surface recrystallization of a uniform layer to about a .56mm (.022") depth had occurred as shown in Figure 32a. A microhardness survey indicated the recrystallized layer to be 48Rc. The microstructure of No. 19 and nature of cracking is shown in Figure 32b. As previously described, a recrystallized microstructure is detrimental to the forming of the ODS alloys when transverse strains are encountered. The reason for the glass A coating promoting surface recrystallization at 2100°F is not known, though it could have been a subtle contamination effect which did not show up in the surface chemistry analyses. Fiber frax wrap provided the best insulating qualities. Near-net shape No. 18 visibly retained heat longer than the glass coated or bare parts. However, satisfactory results were achieved without any surface preparation (bare). Surface insulation is not needed in bending LPT vane near net shape when process times are very short.

After bending, the near-net shape were recrystallization heat treated and macrostructurally evaluated. Heat treating was performed using a progressive temperature cycle - 1205°C (2200°F), 1260°C (2300°F and 1315°C (2400°F) for one hour each temperature. The recrystallized macrostructures obtained were categorized as "good", "marginal" or "dual". A "good" macrostructure is one that meets turbine vane specification requirements, i.e., in the recrystallized and macroetched ($HCL+H_2O_2$) condition, the cross-section normal to the process direction shall have a dull matte appearance with no significant differential etching effects and the modulus of elasticity shall not be greater than 17.24×10^4 MPa (25×10^6 psi). The term "marginal" describes a macrostructure which may be acceptable by modulus measurements but lacks a uniformly etched macrostructure. It is not recommended that a "marginal" microstructure be used in engine service and any process that produces a "marginal" macrostructure should be optimized. A "dual" macrostructure is one that has an obviously strong etch mismatch and does not meet either the visual or modulus requirements.

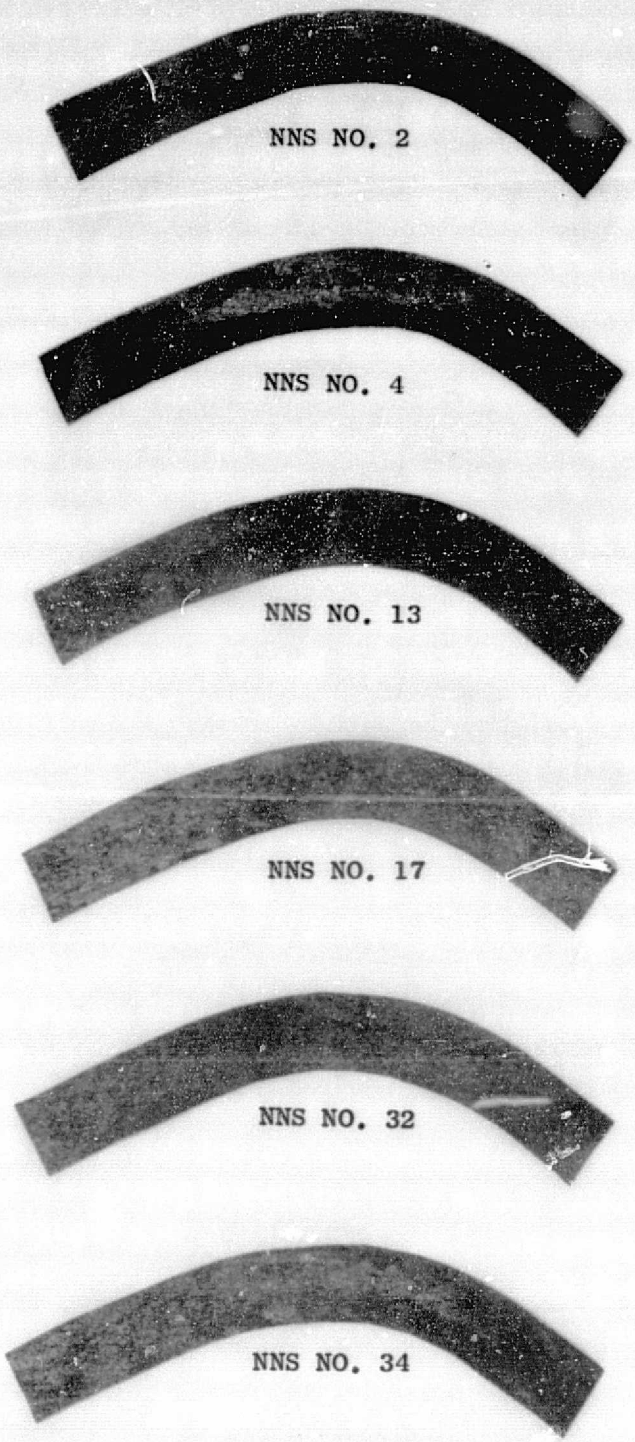
Macrostructures of the NNS transverse cross-sections are shown in Figure 33. Nine of the 18 parts (nos. 2, 4. 5, 13, 16, 17, 25, 32 and 34) evaluated (#6 was retained by TRW) contained the desired macrostructure. Five (#14, 15, 18, 20 and 29) recrystallized to a marginal macrostructure. Four (nos. 1, 3, 19 and 28) contained the unacceptable dual macrostructure. Although 14 of the 18 evaluated near-net shapes would probably meet the component specification modulus requirements, it was recognized that further optimization would be required.



a. Uniform Layer Observed on Piece 19. 100X

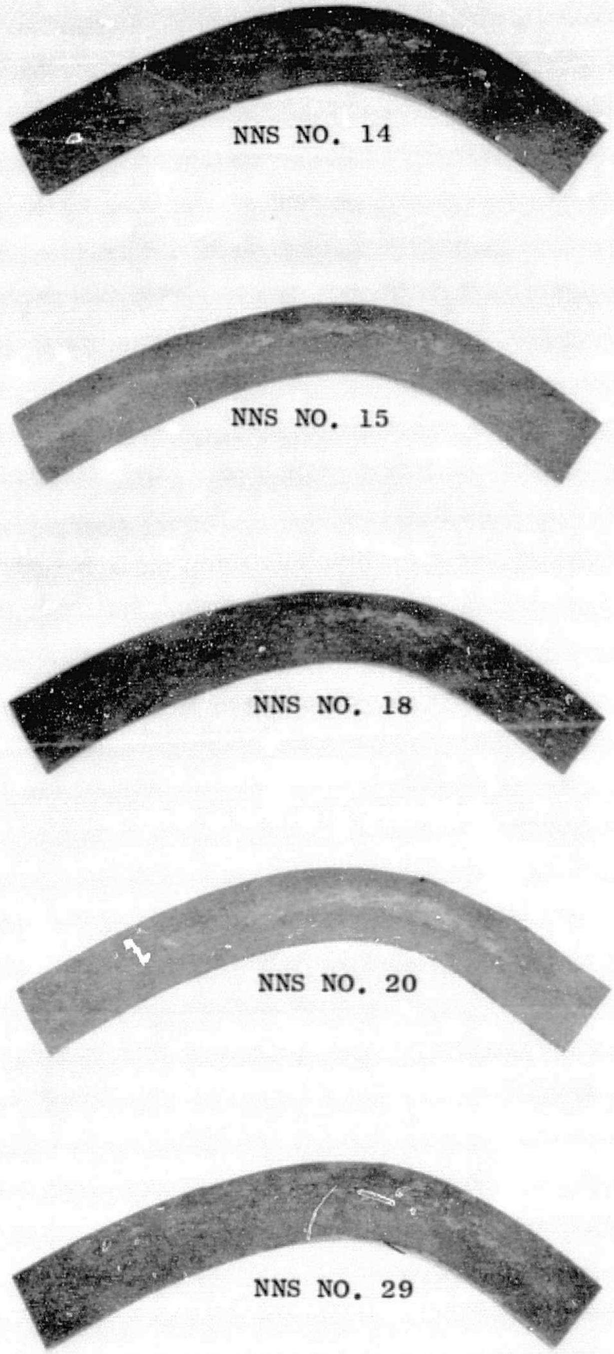
b. Typical Surface Tears 80X

Figure 32 Surface Condition of MA757 NNS No. 19 After Bending at 2100°F Using Glass Composition A



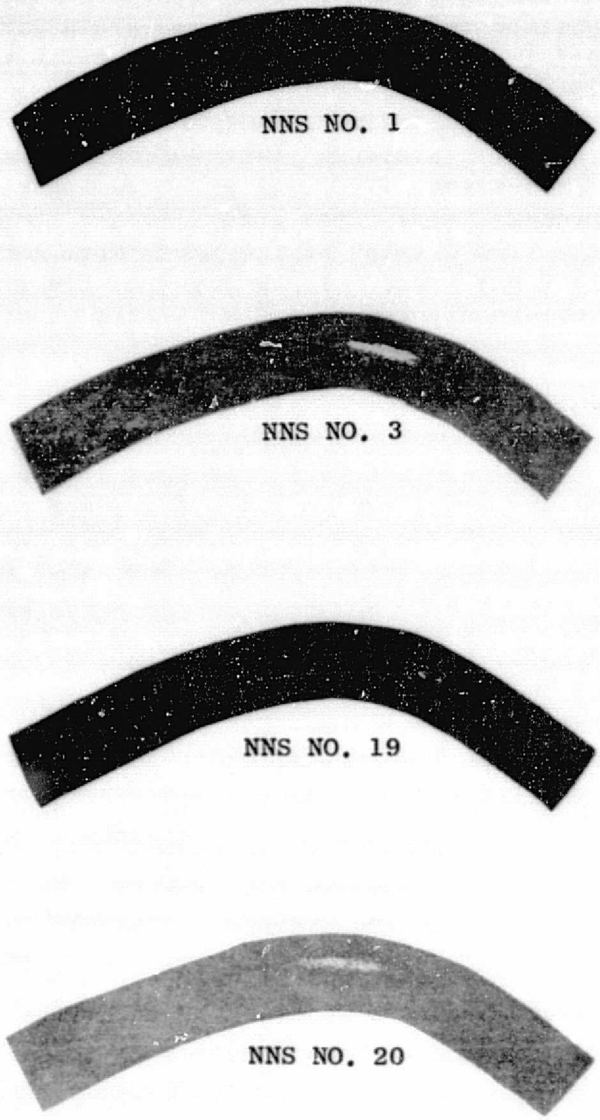
(a) GOOD STRUCTURE

Figure 33 MA757 NNS Macroetched Transverse Cross Sections 1.5X



(b) MARGINAL STRUCTURE

Figure 33 Continued



(c) DUAL (UNACCEPTABLE) STRUCTURE

Figure 33 Continued

Longitudinal and transverse macrostructure and microstructures typical of the MA757 NNS are shown in Figure 34 and Figure 35 respectively. Samples are in the etched condition and show the desired grain size and shape. Crystallographic orientation direction is not evident in the photomicrographs but readily distinguishable in the macro-etched condition.

Several General Electric prepared plate segments were bent to a simulated NNS prior to the TRW processing. The bending operation was improvised. Unlike the fast TRW process, bend rates were slow and temperatures probably somewhat lower than the 1150°C (2100°F) the parts were heated to even though they were wrapped with fiber frax. All the General Electric bent shapes exhibited the desired texture after a recrystallization heat treatment and macroetch.

YDNiCrAl Bend Processing

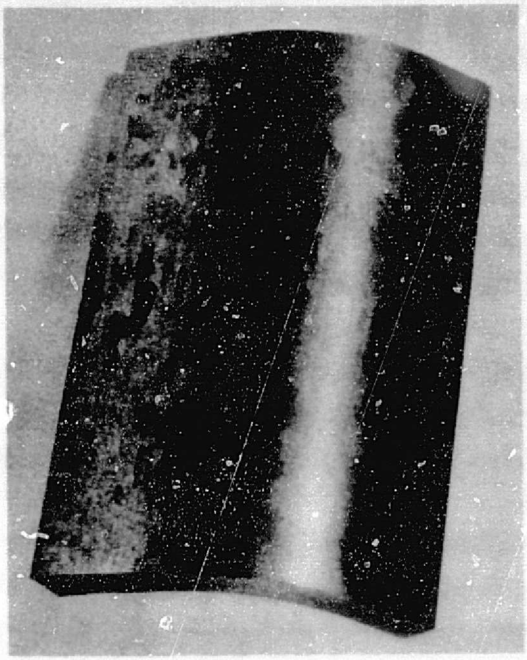
Eleven YDNiCrAl plate segments were processed to the F101 LPT vane NNS. The process conditions are indicated in Table IX. Bend temperatures were 1120°C (2050°F), 1150°C (2100'F), and 1175°C (2150°F). Good shape and integrity were produced at all three temperatures. The only cracking detected was on the convex side of near-net shapes #21, and 22 where glass B coating was used at 1150°C (2100°F). The same result was noted on MA757 coated with glass A and bent at 1150°C (2100°F). This cracking reinforced the conclusion that ODS NiCrAl alloys were not compatible with the glass coatings at temperatures of 1150°C (2100°F), or above. Both alloys (NNS #32 and 33) bent well at 1120°C (2050°F) with glass coating. The typical macrostructure and microstructures of the YD NNS obtained after a recrystallization heat treatment and etch are shown in Figure 36 and 37 respectively. All YDNiCrAl NNS examined contained the unacceptable dual structure which is believed to be caused mainly by an improper selection of the plate rolling temperature. It is also believed that with the correct rolling and bending temperatures, YDNiCrAl could successfully be processed to NNS and contain the desirable microstructure and crystallographic orientation. Although the YDNiCrAl structures were determined to be unacceptable, the NNS were evaluated in tensile and stress rupture.

MA754 Bend Processing

For information, MA754 (Ni-20Cr-0.6-Y_2O_3) was included in the Task II NNS process establishment, though this effort was outside the scope of the program. The MA754 plate rolling and bending was performed using the conditions established for MA757 (Ni-16 Cr-4Al - 1Y_2O_3 alloy. No attempt was made to tailor the process temperatures for the MA754.

A 30.5mm thick x 73.7mm wide x 15.2 cm long (1.2 in x 2.9 in x 6 in) bar was rolled at 1010°C (1850°F) to a 7.6mm (.3") thickness. Rolling was conducted with the steel clad intact, using 10% reductions and was reheated each pass. The rolled plate was pickled, cut to preform shape, bent to NNS and recrystallized. The annealing heat treatment was a progressive cycle of 1205°C, 1260°C and 1315°C (2200°F, 2300°F and 2400°F) for one hour each temperature.

Characterization of the MA754 NNS processed parts indicated good integrity and precision shapes were obtained. Macroetching and conical shaped indentor



LONGITUDINAL

ORIGINAL PAGE IS
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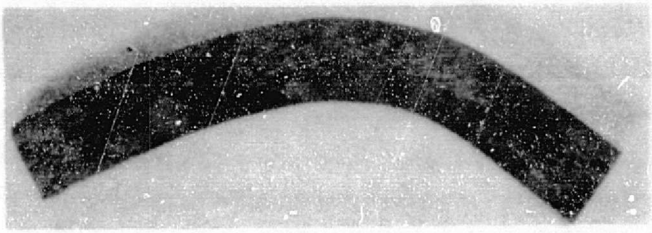
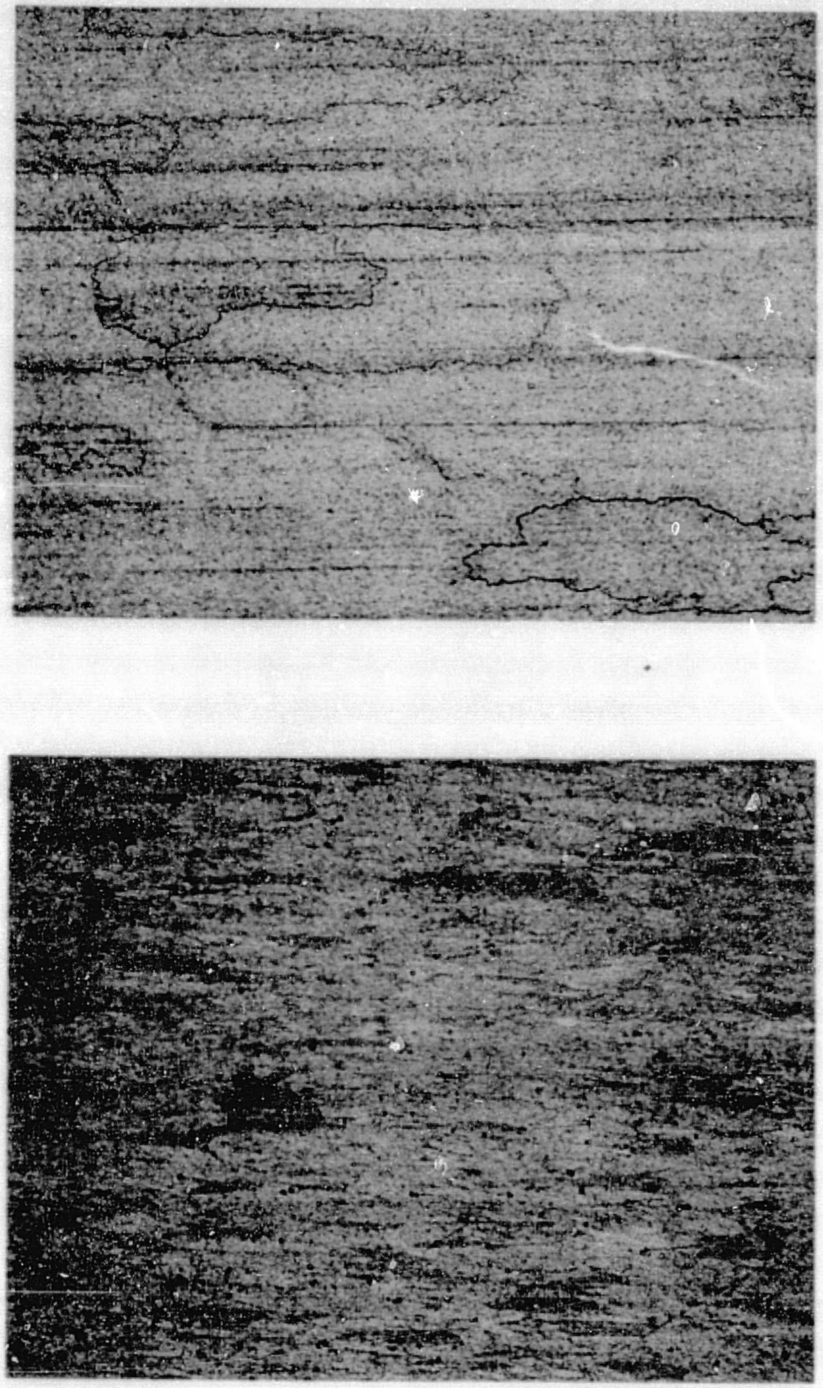


TRANSVERSE

Figure 34 Typical MA757 NNS Macrostructure



LONGITUDINAL

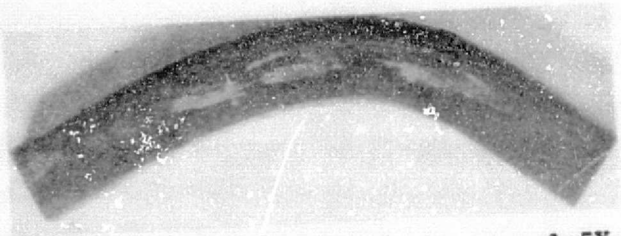
TRANSVERSE

100X

50 HDO_3 - 50 ALCOHOL

Figure 35 Typical MA757 NNS Microstructures

NNS NO. 10

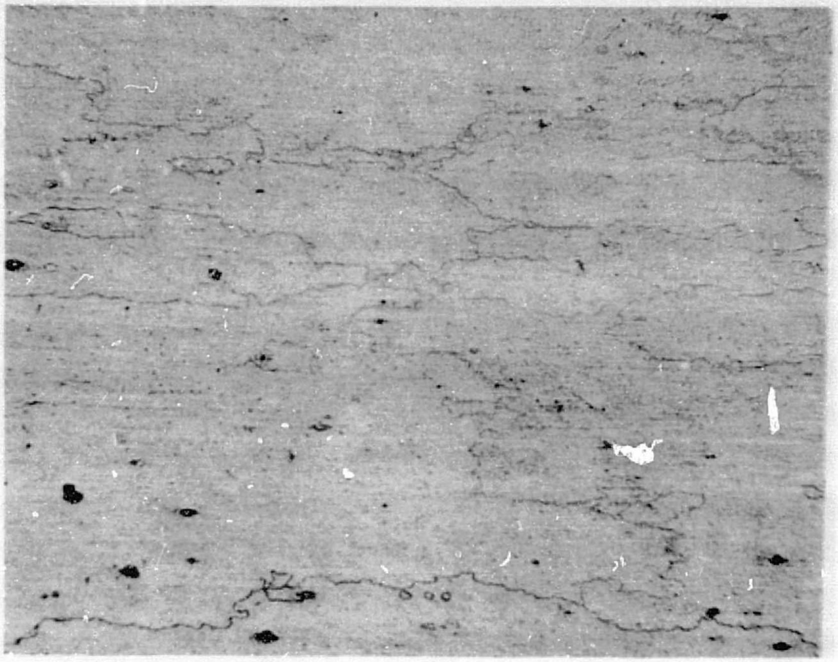


1.5X

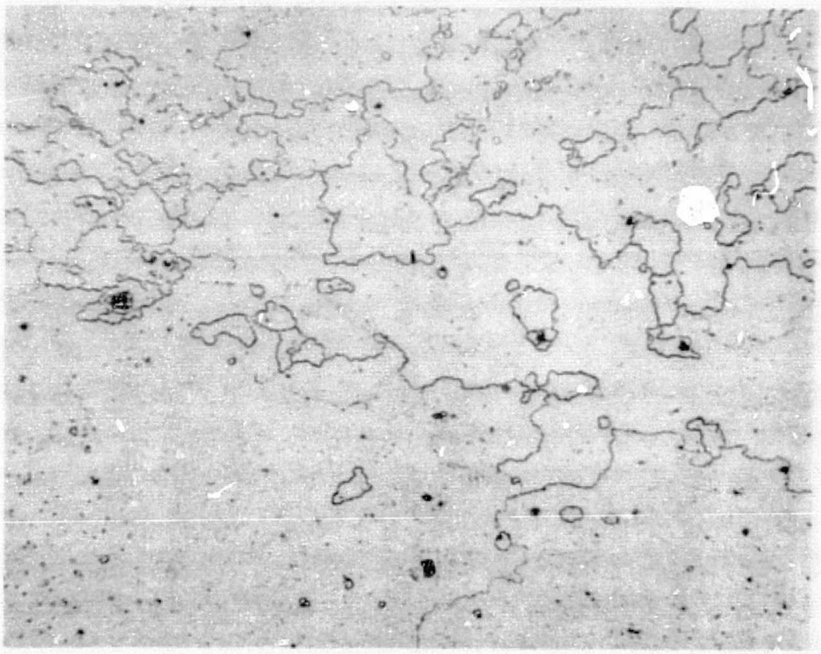
NNS NO. 33

DUAL (UNACCEPTABLE) STRUCTURE

Figure 36 YDNiCrAl NNS Macroetched Transverse Cross-Sections



LONGITUDINAL



TRANSVERSE

50 HNO_3 - 50 ALCOHOL 100X

Figure 37 YDNiCrAl NNS Microstructures

penetrations indicated the desirable (001) crystallographic orientation was not obtained. It is believed MA754 can be successfully NNS processed by simply selecting the proper plate rolling temperature. Subsequent investigations determined MA754 to have more tolerance for conversion than the NiCrAl-Y_2O_3 alloys, but it requires a different process temperature.

In a General Electric ODS Turbine Nozzle Manufacturing Program (AFML F33615-76-C-5235) F101 HPT vanes were successfully forged from wedge shaped preforms, diagonally cut from rectangular bar.

2.5.4 Near-Net Shape Characterization

Tensile Evaluation. Longitudinal and long transverse tensile specimens were prepared from flat (unstrained during bending) and bent (strained during bending) regions of the MA757 NNS and tensile tested at RT and 1093°C (2000°F) as shown in Table X. The test results were compared to vendor furnished baseline data typical of properties achieved in 30.5mm (1.2") thick x 76.2mm (3.0") wide rectangular bar. Rectangular MA754 bar is currently the mill product produced by Huntington Alloys, Inc., to General Electric specification and used in the manufacture of vanes. Tensile specimen designs were the same as used in the Task I properties evaluation and were described in Section 2.4.5. The cross-sectional ratio of the .160" gage diameter and even the .100" gage diameter of the long transverse specimens proved not to be large enough for the RT testing. Three of the four longitudinal test specimens failed in the threaded section indicating some sensitivity of the ODS alloys to notch effects at room temperature. Therefore, only limited RT property comparisons could be made. Longitudinal test specimens No. 9 machined from the flat region of the NNS failed in the gage section. Based on the single results yeild strength was indicated to be about 151.7MPa (22 ksi) lower than the average baseline data. Ultimate strength and ductilities indicated to be improved about 75.8 MPa (11 ksi) and 8% (elongation) respectively. Specimens #10, 11 and 12 tested at RT failed in the threads. The only indications possible were that the RT averaged ultimate strengths were greater than 1151.3 MPa (167 ksi). Specimens from the transversely strained NNS regions appear to have ultimate strength levels comparable to the unbent regions. Limited tensile testing of ODS alloys in general has been conducted and strength variances are not defined.

Longitudinal specimens #13, 14, 15 and 16 were tensile tested at 1093°C (2000°F) and compared to baseline data. Nos. 13 and 14 were prepared from the flat region of the NNS and 15 and 16 from the radiused regions. All four specimens produced similar tensile properties indicating that bending had no effect on longitudinal tensile properties and were representative of rolled and recrystallized MA757 plate properties. The tests results when averaged indicated a yield strength of 82.0 MPa (11.9 Ksi) an ultimate of 92.4 MPa (13.4 ksi), elongation of 21.4% and reduction of area of 60.3%. Compared to the baseline data furnished by the vendor the strengths maintained in the NNS were lower and ductilities were considerably higher. However, the vendor tensile data was limited and is higher than expected. HDA8077 alloy, similar in composition and preparation, has strength levels of about 100.0 MPa (14.5 ksi) ultimate and 14% elongation. It is believed the tensile strengths were maintained in the NNS process and ductilities were improved.

TABLE X ODS ALLOY LPT VANE NEAR-NET SHAPE TENSILE PROPERTIES

S.N.	Material[1]	NNS Sampling Location	Test Direction	Test Temp. °C (°F)	0.2% Yd Str. MPa (ksi)	Ult. Str. MPa (ksi)	El.,%	R.A.,%
-	MA 757	Baseline[2]	L	RT	~896.2 (130.0)	~1137.5(165.0)	~ 4.0	~ 2.0
9	MA 757	Flat[3]	L	RT	747.3 (108.4)	1216.1(176.4)	12.3	15.3
10	MA 757	Flat	L	RT	-	>1102.4(159.9)	Thread Failure	
11	MA 757	Radiused[4]	L	RT	-	>1187.1(172.2)	Thread Failure	
12	MA 757	Radiused	L	RT	-	>1156.1(167.7)	Thread Failure	
-	MA 757	Baseline	L	1093 (2000)	~103.4 (15.0)	~117.2(17.0)	~ 9	-
13	MA 757	Flat	L	1093 (2000)	80.0 (11.6)	91.7(13.3)	21.1	57.1
14	MA 757	Flat	L	1093 (2000)	84.8 (12.3)	94.4(13.7)	22.5	68.2
15	MA 757	Radiused	L	1093 (2000)	79.3 (11.5)	91.0(13.2)	22.9	59.4
16	MA 757	Radiused	L	1093 (2000)	84.8 (12.3)	91.0(13.2)	19.0	56.4
-	MA 757	Baseline	LT	RT	~861.8 (125.0)	~1054 (153.0	~ 7.0	~ 7.0
17	MA 757	Radiused	LT	RT	-	>890.0(129.1)	Thread Failure	
-	MA 757	Baseline	LT	1093 (2000)	~96.5 (14.0)	~103.4(15.0)	~ 2	-
19	MA 757	Flat	LT	1093 (2000)	93.1 (13.5)	99.3(14.4)	26.7	8.9
20	MA 757	Radiused	LT	1093 (2000)	82.7 (12.0)	97.9(14.2)	25.3	8.9
21	MA 757	Radiused	LT	1093 (2000)	90.3 (13.1)	100.0(14.5)	28.0	10.1
-	YD NiCrAl	Baseline	L	1093 (2000)	-	~82.7(12.0)	~20	~28
28	YD NiCrAl	Flat	L	1093 (2000)	74.4 (10.8)	82.0(11.9)	14.6	39.7
29	YD NiCrAl	Radiused	L	1093 (2000)	75.1 (10.9)	84.1(12.2)	18.1	29.9
-	YD NiCrAl	Baseline	LT	1093 (2000)	-	86.2(12.5)	8.8	6.3
31	YD NiCrAl	Flat	LT	1093 (2000)	92.6 (13.4)	98.6(14.3)	19.3	6.5
32	YD NiCrAl	Radiused	LT	1093 (2000)	87.6 (12.7)	92.4(13.4)	26.7	16.5

(1) Recrystallized condition - 1205°C (2200°F), 1260°C (2300°F) and 1315°C (2400°F), for one hr. each temp.

(2) Vendor furnished data, typical of 30.5 mm (1.2") thick x 76.1 mm (3.0") wide size bar.

(3) Tensile specimen prepared from flat region of NNS - not transversely strained during bending.

(4) Tensile specimen prepared from radiused region of NNS - transversely strained during bending.

Specimens #17, 19, 20 and 21 were prepared (assembled and brazed) to evaluate the long transverse MA757 NNS microstructure of the flat and radiused regions. Specimens No. 17, prepared from the bent region was tested at RT and failed in the thread region. The ultimate strength was determined to be greater than 889.3 MPa (129.0 ksi). Specimen #19, 20, and 21 were tested at 1093°C (2000°F). No. 19 was prepared from the bent region. All three specimens produced comparable properties. Yield strengths averaged 88.9 MPa (12.9 ksi), ultimate strength of 99.3 MPa (14.4 ksi), elongation of 26.7% and 9.3% reduction of area. Compared to the baseline vendor data, the NNS strengths were similar and the ductilities were significantly improved. It is believed that longitudinal and long transverse tensile strengths at RT and 1093°C (2000°F) were maintained in NNS plate rolling and bending and ductilities were significantly improved when tested in tension.

The YDNiCrAl LPT vane NNS were tensile evaluated in the same manner as the MA757 NNS. Longitudinal and long-transverse tensile specimens were prepared from flat and rediused regions of the NNS, tested at 1093°C (2000°F) and compared to baseline data. Specimens No. 28 prepared from the flat region and No. 29 from the radiused region, indicated nearly equivalent longitudinal strengths and ductilities and appeared to be similar to baseline data. The tensile tests results indicate YDNiCrAl alloy also can be rolled and bent to NNS and maintain tensile properties comparable to rectangular shaped bar.

Stress Rupture Evaluation. The MA757 and YDNiCrAl F101 LPT vane NNS were evaluated in 1093°C (2000°F) stress rupture as shown in Table XI. Specimens were prepared to evaluate properties in the longitudinal and long transverse directions in the flat (not transversely strained during bending) and bent (transversely strained during bending) regions as shown previously in Figure 23. MA757 longitudinal specimens No. 1 through 4 were direct loaded at 68.9 MPa (10 ksi). Specimens #1 and #2, prepared from the flat region, had rupture lives of 69 hours and 90 hours respectively. Specimens #3 and #4, prepared from the bent region had lives of 16 hours and 28 hours respectively. Rupture lives of specimens #3 and #4 were slightly lower than lives for specimens 1 and 2, but this was not believed to be an unusual variation. All of the longitudinal specimens indicated strengths comparable to the baseline. Ductilities were slightly improved.

MA757 long transverse specimens #5 through 8 were rupture tested at 1093°C (2000°F). Nos. 5, 6, and 8 were step loaded to expedite testing. Although the initial stresses and times at temperatures prior to step loading undoubtedly had some effect on the rupture lives, only the highest stressed conditions of the step loaded tests were compared to baseline data. Specimens No. 7 and 8 prepared from the radiused regions lasted 5 hours and 34 hours at 27.6 MPa (4.0 ksi). All four MA757 long transverse rupture specimens had strengths comparable to baseline data of about 30 hours at 27.6 MPa (4.0 ksi). Because of the nature of the specimen fractures, the elongation and reduction of areas could not be measured on most of the long transverse failures.

TABLE XI - ODS ALLOY LPT VANE NEAR-NET SHAPE STRESS RUPTURE PROPERTIES

S.N.	Material[1]	NNS Sampling Location	Test Direction	Test Temperature °C	(°F)	Stress, MPa (ksi)	Life Hours	El. %	R.A., %
-	MA 757	Baseline[2]	L	1093	(2000)	68.9 (10)	30	3	6
1	MA 757	Flat	L	1093	(2000)	68.9 (10)	69	7	19
2	MA 757	Flat	L	1093	(2000)	68.9 (10)	90	11	23
3	MA 757	Bent (4)	L	1093	(2000)	68.9 (10)	16	10	26
4	MA 757	Bent	L	1093	(2000)	68.9 (10)	28	7	10
-	MA 757	Baseline	LT	1093	(2000)	27.6 (4.0)	30	5	1
5	MA 757	Flat	LT	1093	(2000)	24.1 (3.5)	137	load increased to 4.0 ksi	
						27.6 (4.0)	56	NA	NA
6	MA 757	Flat	LT	1093	(2000)	27.6 (4.0)	193	load increased to 4.5 ksi	
						31.0 (4.5)	11	10	NA
7	MA 757	Bent	LT	1093	(2000)	27.6 (4.0)	5	NA	NA
8	MA 757	Bent	LT	1093	(2000)	24.1 (3.5)	284	load increased to 4.0 ksi	
						27.6 (4.0)	34	NA	NA
-	YD-NiCrAl	Baseline	L	1093	(2000)	51.7 (7.5)	50	9	3 to 60
22	YD-NiCrAl	Flat	L	1093	(2000)	48.3 (7.0)	212	load increased to 7.5 ksi	
						51.7 (7.5)	67	6	11
23	YD-NiCrAl	Bent	L	1093	(2000)	48.3 (7.0)	354	load increased to 7.5 ksi	
						57.1 (7.5)	408	load increased to 7.5 ksi	
						55.1 (8.0)	431	load increased to 7.5 ksi	
						56.8 (8.5)	442	7	21
-	YD-NiCrAl	Baseline	LT	1093	(2000)	34.5 (5.0)	180	5	3
24	YD-NiCrAl	Flat	LT	1093	(2000)	34.5 (5.0)	7	1	NA
25	YD	Bent	LT	1093	(2000)	31.0 (4.5)	65	9	NA

(1) Recrystallized condition

(2) Vendor furnished data, typical of 30.5 mm (½") thick x 76.2 mm (3.0") wide size bar.

(3) Tensile specimen prepared from flat region of NNS - not transversely strained during bending.

(4) Tensile specimen prepared from bent ragion of NNS - transversely strained during bending.

YDNiCrAl specimens were prepared and the longitudinal and long transverse microstructures were stress rupture evaluated at 1093°C (2000°F). Longitudinal specimens #22 and #23, prepared from flat and bent regions of the NNS, were tested in a step load manner. Specimen No. 22 had 67 hours rupture life at 51.7 MPa (7.5 ksi). Specimen No. 23 indicated 11 hours life at 58.60 MPa (8.5 ksi). The tests results compared to the baseline for approximately 50 hours rupture life at 51.7 MPa (7.5 ksi) load indicated the longitudinal strengths were maintained.

Long transverse YDNiCrAl specimens from flat and bent NNS regions were 1093C (2000°F) stress rupture evaluated in specimens #24 and 25. No. 24 prepared from the flat region lasted 7 hours at 34.5 MPa (5.0 ksi) No. 25 prepared from the bent region lasted 65 hours at 31.0 MPa (4.5 ksi). Compared to the long transverse baseline of about 180 hours at 34.5 MPa (5.0 ksi), the NNS indicated a slightly lower strength. Although it is believed that if the YDNiCrAl desirable microstructure was maintained through the plate rolling and bending process the long transverse strengths would have been at least as high as in the 30.5mm (1.2") thick x 76.2mm (3.0") wide baseline rectangular shaped YDNiCrAl strength.

NNS Modulus of Elasticity. Longitudinal modulus of elasticity values of the MA757 NNS with the desirable microstructure were established using the sonic test technique described in Section 2.4.5. Test pins from flat and bent regions were tested dynamically from RT to 982C (1800°F) and the results are shown in Figure 38. The results from the flat region are representative of the plate processing and the results of the bent region representative of the bend processing. The data are nearly superimposed indicating nearly equivalent modulus values from both NNS regions. The results also show the modulus values are low and typical of a face centered cubic (001) crystallographic orientation.

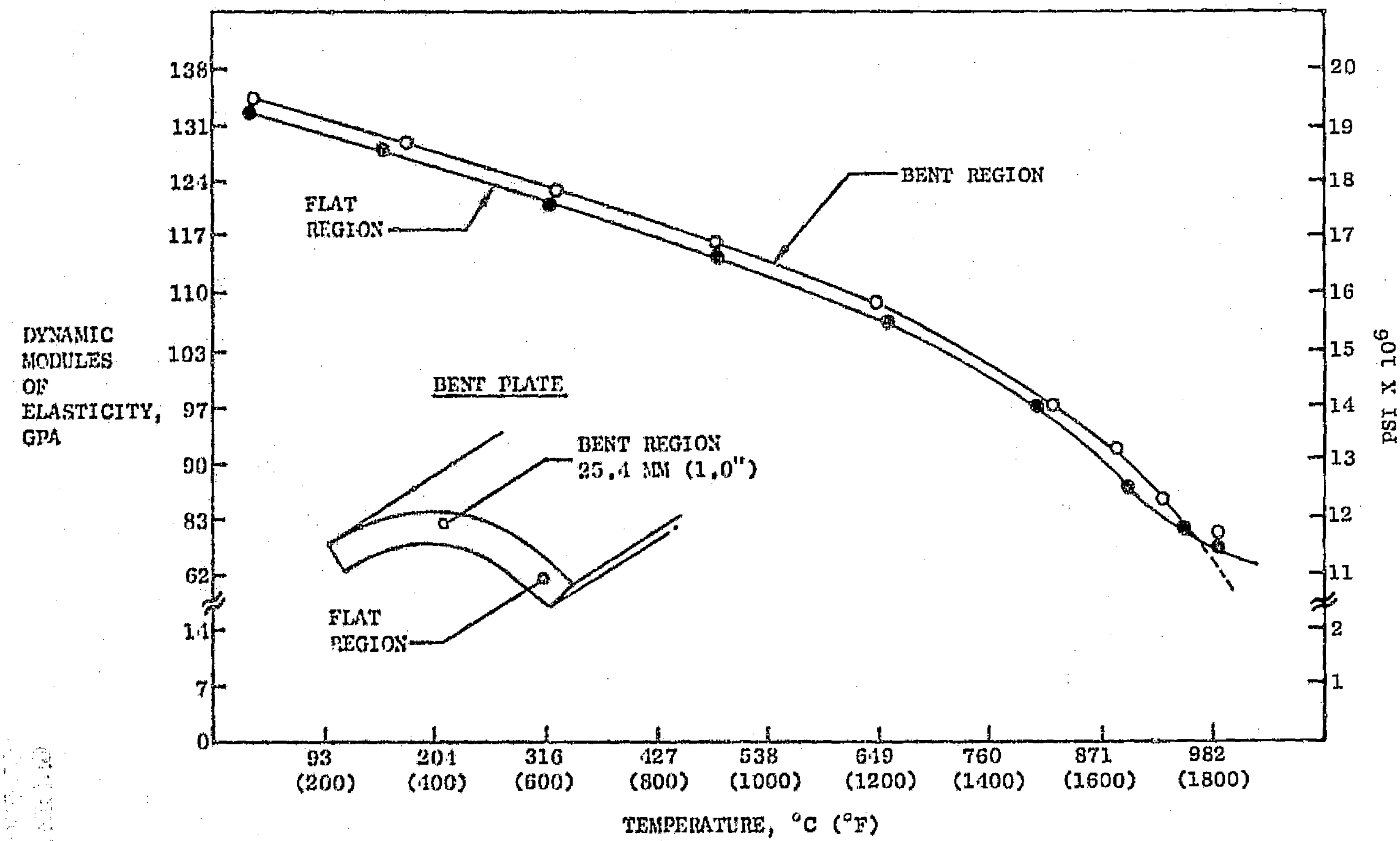


Figure 38 MA757 LPT Vane NNS Longitudinal Dynamic Modulus

3.0 ESTABLISHED PROCESS FOR NNS VANES

A plate bending process has been established for the preparation of F101 LPT vane NNS segments. The bent plate is an "economic" shape, i.e., high material utilization with low process cost. The process, illustrated in Figure 39, is amenable to all ODS alloys.

NNS processing was performed as indicated in(Section 6.0 of this report) Preliminary Manufacturing Process, Material Specification and Quality Control Procedures and described below:

- MA757 was procured in as-hot-rolled (unrecrystallized) rectangular shaped bar with the steel extrusion jacket intact. The material was processed by the vendor to fulfill the requirements of Preliminary Product Specification (Section 7.0), after recrystallization heat treatment.

- Plate processing was performed by hot rolling unrecrystallized ODS alloy bar to a nominal 7.37mm (0.29 in.) thickness x 66.55mm (2.62 in.) wide x 88.9mm (3.5 in.) multiple lengths. The plate rolling temperature and reduction rate were selected to maintain recrystallization response consistent to vendor mill product. Good results were obtained with MA757 rolled at 1010°C to 1023°C (1850°F to 1875°F) using 10% reductions and reheating each pass. Removal of the steel extrusion clad was accomplished by pickling in 50-50 nitric acid and water solution.

- MA757 blanks for bend processing to NNS were prepared by cutting the rolled plate to nominal 55.88mm (2.200 in.) widths x 82.169mm (3.235 in.) lengths. Surface defects did not exceed 0.254mm (0.010 in.) depth.

- NNS processing was performed in TRW prepared tooling No. 9942M44 heated to about 205°C (400°F). Unclad, non-coated blanks were heated to 1120°C to 1150°C (2050°F to 2100°F) in an electric furnace for fifteen minutes and bent to shape. Part transfer and bending times were eight seconds or less.

- Part cleaning was accomplished by grit blasting.

- NNS part heat treatment was conducted using a progressive temperature cycle - 1205°C (2200°F), 1260°C (2300°F) and 1315°C (2400°F) for one hour at each temperature. Simplified heat treatments of 1315°C (2400°F) for one hour were also determined to be satisfactory in most cases.

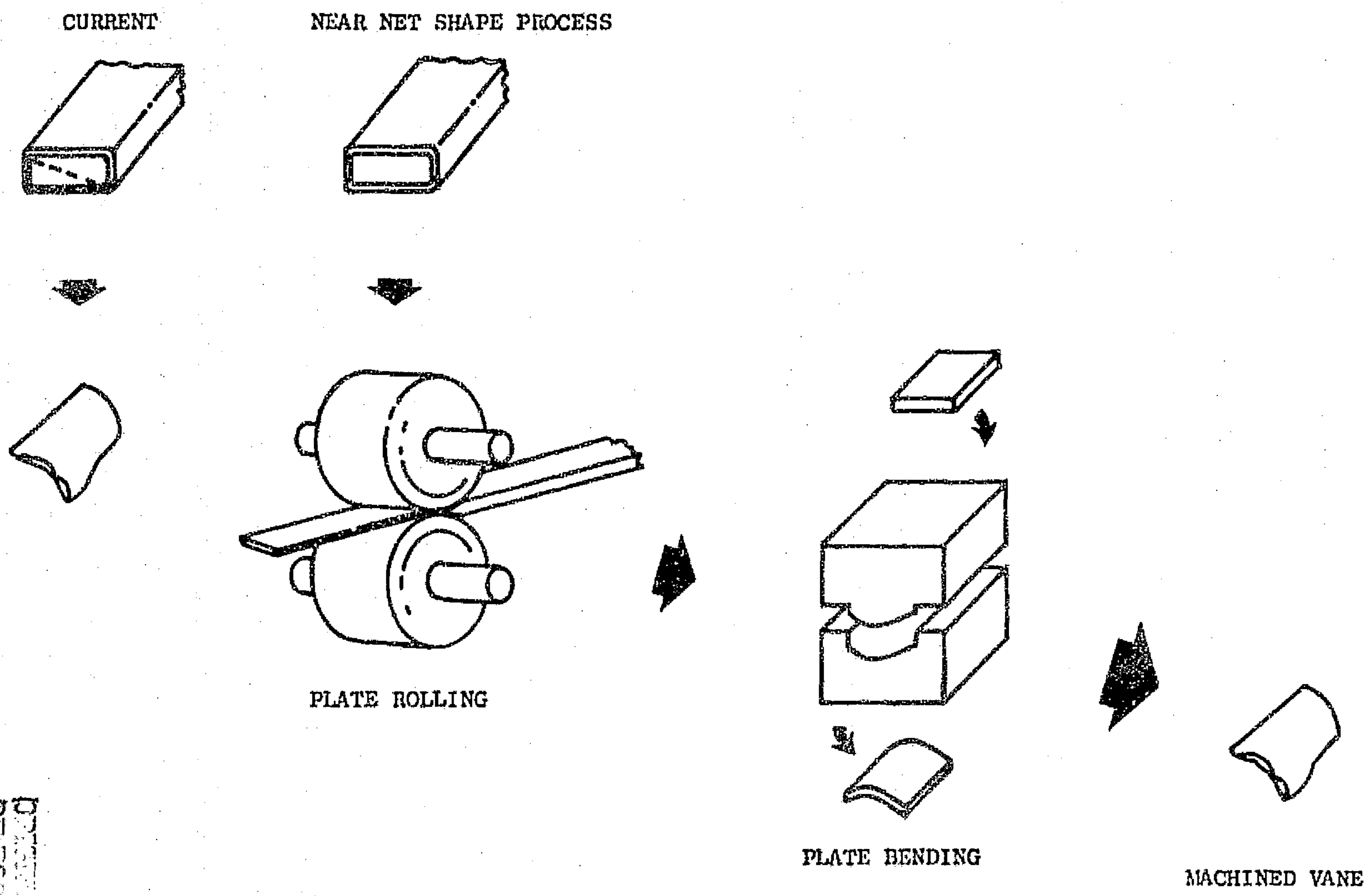


Figure 39 ODS Alloy NNS LPT Vane Manufacturing Process

4.0 CONTINUING WORK

The plate bending process and directional forging technology established in this program will be utilized in General Electric's current AFML Manufacturing Technology Program (F33615-76-C-5235). F101 HPT band and LPT vane NNS will be prepared by the plate rolling and bending process. F101 HPT vane NNS will be prepared by forging wedge shaped preforms, diagonally cut from rectangular shaped bar. The NNS will be machined to finished parts and engine tested.

5.0 CONCLUSIONS

- Hot plate bending is a more attractive NNS process because the F101 LPT vane has a relatively constant thickness (except for the trailing edge).
- Plate bending is capable of imparting vane required curvatures and twist.
- Plate bending preforms must be processed in the as-rolled unrecrystallized) form.
- Preparation of ODS plate for bending is a straightforward process using currently available nominal 30.5 cm x 76.2 cm (1.2 inch x 3.0 inch) bar in the unrecrystallized form, providing reheating between roll passes is available.
- Plate bending does not measurably affect the microstructure or properties of the ODS plate.
- Directional forging is a viable NNS process for ODS vanes and more attractive than bending for vanes with large section thickness variations from leading to trailing edges.
- Recrystallized preforms can be used for directional forging to enhance workability provided transverse strains are kept compressive.
- Bare extrusion of a shaped preform is the least attractive of the three processes studied because it requires precision preforms and demands more workability than the other processes.
- ODS preform materials for NNS should be capable of meeting specification property and microstructure requirements. The NNS process should not be relied on to cure or tailor the preform.
- Cladding, ceramic, and refractory insulating materials can be effective in reducing heat losses in transfer and die contact, though reactions which cause surface recrystallization must be guarded against.
- MA956 (ODS-FeCrAl) has considerably more workability even in the unclad condition than do the ODS-NiCrAl alloys.
- Extrusion and directional forging under the conditions evaluated are incapable of producing the desired (001) texture in MA956.

6.0 PRELIMINARY MANUFACTURING PROCESS, MATERIAL SPECIFICATION AND QUALITY CONTROL PROCEDURES

Preliminary Manufacturing Process

The preliminary process outlined below is recommended for the manufacture of MA757 LPT vane NNS. The process is outlined in a flow chart in Figure 40.

1. Alloy - to be purchased to the following composition:

Ni - Balance	C - 0.10 maximum
Cr - 14.00 to 18.00	S - 0.015 maximum
Al - 3.80 to 5.50	O - information only

2. Material Form - material to be procured as hot rolled (unrecrystallized) plate.

3. Plate Processing - to be by extrusion and hot flat rolling to plate configuration, nominally 7.37mm (0.29 inch) thick x 66.55 mm (2.62 inch) wide in multiple lengths of 88.9 mm (3.5 inch).

4. Property Requirements - the plate shall be capable of meeting all property requirements specified in the Preliminary Product Specification when given a subsequent recrystallization heat treatment.

5. Material Condition - to be procured as-rolled (unrecrystallized) and decanned by pickling in 50-50 nitric acid and water solution.

6. Blank Preparation - NNS preforms to be 55.88mm (2.200 inch) + .000mm (.000 inch) - .254mm (.010 inch) widths x 82.169mm (3.235 inches) lengths for bending.

7. NNS Processing - to be performed in TRW tooling No. 9942M44, or equivalent design, heated to about 205°C (400°F). Heat unclad, noncoated MA757 NNS preforms to 1120°C - 1150°C (2050°F - 2100°F) in an electric furnace for fifteen minutes and bend to NNS. Part transfer and bending times should be kept to a minimum - approximately eight seconds total.

8. Part Cleaning - to be accomplished by grit blasting.

9. Heat Treatment - 1205°C (2200°F), 1260°C (2300°F) and 1315°C (2400°F) for one hour each temperature.

FIGURE 40

FLOW CHART OF PRELIMINARY MANUFACTURING PROCESS FOR F101 LPT VANE LOW COST MANUFACTURING

MA 757 Powder

Canning

Extrusion

Flat Rolling

Decanning

Blank Preparation

NNS Bending

Recrystallization Heat Treatment

Finished Part Machining

7.0 PRELIMINARY PRODUCT SPECIFICATION

The requirements listed below are recommended as a preliminary specification for low cost F101 LPT vanes through NNS processing.

1. SCOPE

1.1 Scope - This specification presents requirements for MA757 alloy vanes.

1.1.1 Classification - This specification contains the following class:

Class A

1.2 Definitions - For purposes of this specification, the following definitions shall apply:

Primary Material - extruded and rolled 30.5 mm (1.2 inch) thick x 73.7 mm (2.9 inch) wide rectangular MA757 as-rolled (unrecrystallized) bar.

Plate Preform - The individual plate section prepared for bend processing to NNS.

Bend - The forming operation to achieve the precise curvature and twist of the NNS.

NNS - A bent plate section closely approximating the vane configuration for high material utilization.

Run - A batch of blanks that are NNS processed at one time.

Recrystallization - Formation of the desired grain size, shape and crystallographic orientation by heat treatment.

Class A - Hot finished, fully heat treated and capable of 76 Mpa (11 ksi) longitudinal rupture strength at 1093°C (2000°F) for 20 hours.

2. APPLICABLE DOCUMENTS

2.1 The following documents shall form a part of this specification to the extent specified herein.

American Society for Testing and Materials

ASTM E139 Conducting Creep, Creep Rupture and Stress Rupture Tests of Metallic Materials

ASTM E21 Elevated Temperature Tests of Metallic Materials

3. PRIMARY MATERIAL REQUIREMENTS

3.1 Chemical Composition, Percent

3.1.1 Material supplied to this specification shall have the following composition as determined in the input powder lot:

Nickel	Balance	Carbon	0.10 max.
Chromium	14.00 - 18.00	Sulfur	0.015 max.
Aluminum	3.80 - 5.50	Total Oxygen	(1)

(1) Shall be reported for information only.

3.1.2 The analysis made by the manufacturer to determine the percentages of elements required in the powder lots by this specification shall conform to the requirements of 3.1.1 and shall be reported in the certificate of test specified herein. An analysis shall be made on each extrusion, after decanning, for the carbon, sulfur and oxygen content, and the percentages of these elements shall conform to the requirements of 3.1.1 and shall be reported in the certificate of test.

3.1.3 An analysis may be made on a sample blank by the Purchaser and the Chemical composition thus determined shall conform to the requirements of 3.1.1.

3.2 Material Condition

3.2.1 Material shall be supplied by the primary vendor in the hot finished (unrecrystallized) condition as specified below:

> Material shall be uniform in quality and condition clean, sound, and free from foreign materials and from internal and external imperfections detrimental to performance of parts.

3.3 Mechanical Properties

3.3.1 Stress Rupture

3.3.1.1 Material shall be capable of meeting the following minimum stress rupture requirements at 1093°C (2000°F) subsequent a recrystallization heat treatment.

Test Direction	Stress, MPa (ksi)	Life, Hours	Elongation, Percent
In direction of extrusion	76 (11)	20	2
Transverse direction to extrusion	31 (4.5)	20	-

3.4 Grain Structure

3.4.1 The grain structure after recrystallization, shall be columnar with the long axis parallel to the extrusion direction within seven degrees, with no more than five percent equiaxed grains permitted.

4. NNS REQUIREMENTS

4.1 Chemical Composition, Percent

4.1.1 The NNS material shall have the same compositional requirements as the primary material.

4.1.2 An analysis may be made on a sample NNS by the Purchaser and the chemical composition thus determined shall conform to the requirements of 3.1.1.

4.1.3 Material shall be uniform in quality and condition, clean, sound and free from foreign materials and from internal and external imperfections detrimental to fabrication or to performance of parts.

4.2 Material Condition

4.2.1 Material shall be supplied by the NNS vendor in the recrystallized condition and must meet the requirements of 3.2.1, 3.3.1 and 3.4.

4.3 NNS Configuration

The NNS shall be supplied by the secondary vendor, and be a uniformly thick plate segment bent to the curvature and twist approximating the F101 LPT vane configuration. The tolerances of the NNS shall be as specified on the drawing or as agreed upon by the vendor and the Purchaser.

8.0 ECONOMIC ANALYSIS OF ODS ALLOY PLATE BENDING NEAR-NET SHAPE PROCESS

This program has resulted in the establishment of a preliminary manufacturing process for ODS alloy LPT vane NNS. General Electric working with TRW, Cleveland, as the subcontractor has established a potential F101 LPT vane cost reduction.

The current vane manufacturing method is to procure heavy rectangular shaped bar, diagonally cut and machine two vanes per cross section by conventional machining techniques.

The near-net shape process, as shown in Figure 39, was designed to improve material utilization and reduce machining cost. Plate rolling and bending is a simple, inexpensive process which is amenable to all ODS alloy vendors. The plate bending near-net shape process is believed to be the most cost effective process for the F101 LPT vane. It provides substantial material utilization at low process cost.

ODS alloy LPT vane near-net shapes were cost compared to the current method on the basis of a two-hundred and fiftieth engine and 1976 costs. The analysis is based on processing and machining at General Electric. TRW has indicated the near-net shape forming operation to have a shop cost of $6,which is only a portion of the total cost. It is believed,however, to be in line with the General Electric estimate for a similar portion of the work. The cost comparison is shown in Table XII. The current method required 11.3 kilograms (2.5 pounds) input material for each vane. The near net shape process can produce a vane from 4.1 kilograms (0.9 pounds) of material for a savings of 6.1 kilograms (1.35 pounds) or 278 percent improved material utilization. The additional cost for the conversion to near-net shape is insignificant compared to the material and machining costs savings. NNS processing is estimated to save about forty percent vane manufacturing cost up through the outside contour machining step of vane manufacture.

TABLE XII.

ODS ALLOY F101 LPT VANE MANUFACTURING COST COMPARISON[1]

Item	Current Method	Near-Net Shape Method
Material, lbs.	2.25	0.9
Material Cost	$90	$36
NNS Processing	NA[2]	$11[3]
Machining Cost	$36	$29
Vane Cost	126	$76
Material Savings		60%
Machining Savings		19%
Total Vane Cost Savings		40%

(1) Based on 250th engine, 1976 costs

(2) Not applicable

(3) Mfg. at General Electric. TRW shop estimate was $6 (not a total cost).

9.0 REFERENCES

1. Monal, F. R., "Dispersion Strengthening of Metals", MCIC Report 77-30 April 1977.

2. Bailey, P. G., "Manufacture and Engine Test of Advanced Oxide Dispersion Strengthened Alloy Turbine Vanes" NASA CR-135269 (1977).

3. U.S. Patent 2,972,529 Metal Oxide-Metal Composition

4. U.S. Patent 3,723,092 Composite Metal Powder and Production Thereof (Mechanical Alloying).

5. U.S. Patent 4 010,024.

6. Klingler, L. J., Weinberger, W. R., Bailey, P. G., and Baranow, S., "Development of DsNi-Cr-ThD2 Sheet for Space Shuttle Vehicles", NASA 3-13490 (1972). (MCIC 84821).

7. Klingler, L. J.,Weinberger, W. R.,Bailey, P. G., and Baranow, S., NASA Cr-120796 (1972) and NASA Cr-121164 (1973)

8. Barnett, W. J. and Bailey, P.G., "Manufacture of High Strength TD-Ni-Cr Tubing", AF33 (615)-69-C-1870 (April 1971). (AD885 582)

9. (TRW ODS Work)

10. Allen, R. E., and Perkins, R. J., "ODS FeCrAlY Component Manufacturing Development", N00019-72-C-0397 Final Report 1973.

11. Allen, R. E., and Perkins, R. J., "Strengthening of Fe-Cr-Al-Y Oxidation Resistant Alloy", N00019-72-C-0271 Final Report 1973.